RESULTS - AEROSOL CHARACTERIZATION AND TRANSPORT

This part of the study concerns experiments to characterize Owens (Dry) Lake aerosols at the edges of the lake bed and to measure aerosol transport by remote sensing from ground-based cameras, satellite observations, direct aerosol measurement, and characterization of the Owens (Dry) Lake dusts at receptor areas.

Meteorology of dust transport

Generally, two types of flow patterns occur over the lake bed which are associated with northerly wind. The predominant pattern is a simple flow following the local topography with a split to either side of the Coso Range (Figure 37). Winds may exist on or to either side of the lake bed. Wind direction measurements taken during storm periods at the Lone Pine (fall 1991 only), Olancha, Geomet (spring 1993 only), and Keeler, as well as estimates from time lapse photography, yield average wind directions within 20 degrees of the local topography for 70% of storm periods.

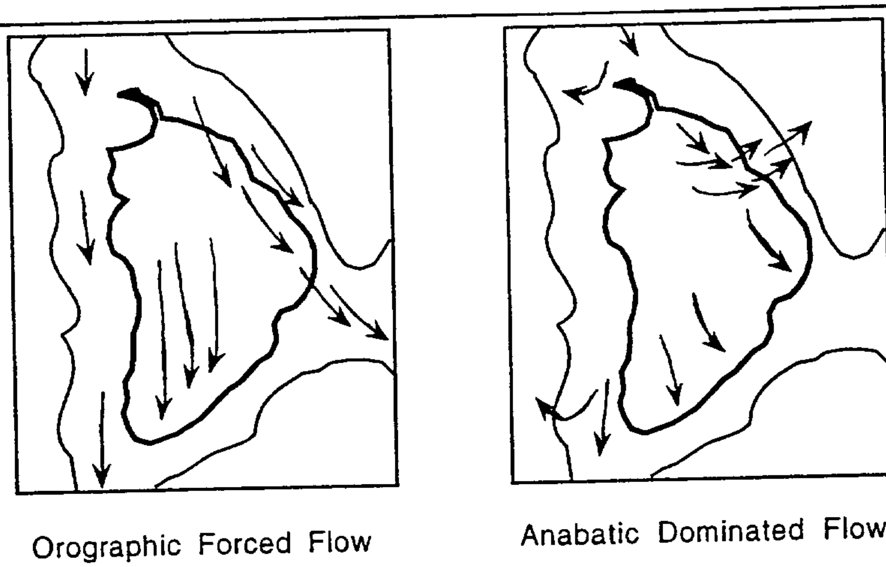


Figure 37. Typical air flow patterns around Owens (Dry) Lake.

The second flow pattern consists of a northerly flow with very strong valley wind (anabatic) components, which are more likely to form at the beginning of this type of flow pattern. Wind directions at Lone Pine and Keeler correspond to the positive slope gradient of the Sierra Nevada and White-Inyo ranges, respectively. The valley wind component of the flow corresponds very strongly to the sun's zenith angle against the mountain ranges. At one point (12:00 p.m., 11/27/91) wind vectors were 174 degrees out of phase between Lone Pine (4 m/s at 107 degrees) and Keeler at (8 m/s at 281 degrees). The valley wind was much stronger along the White-Inyo Range where wind directions in the afternoon were 238 degrees at Keeler and 340 degrees over the northeastern lake bed.

Though the existence of strong valley winds which affect the flow patterns in the center of the valley are rare, time lapse photographs demonstrate the existence of very mild valley winds during most daylight hours on the ranges themselves. Along the Sierra Nevada, dust plumes from the south end of the lake bed were observed moving with a southeasterly wind up the slope of the Sierra Nevada while wind directions at Lone Pine and Olancha, at the base of the range, stayed strictly northerly. These mountain valley interactions were observed transporting large amounts of dust into the Inyo National Forest lands adjacent to the lake.

The WESTEC study (1984) suggested the existence of large horizontal wind gradients across the Owens Valley. During the fall 1991 and March 1993 study period we observed the same phenomenon. During two of the four storms studied in fall 1991, periods existed where wind speeds at Keeler were below 2 m/s while at A-tower, only 5 km away, winds stayed above 11 m/s. For the spring 1993 intensive, while the average daily wind speeds for the sites were similar, examination of the hourly meteorology for dust storm periods shows the wind shifting to different sides of the valley. Scatter plots of wind speed for the spring intensive at the three near-lake bed meteorological towers (Keeler, Geomet, and Olancha, figure 38) show a generally poor correlation between the sites with r around only 0.5. As an example, while the average daily wind speed at the Geomet tower for March 17 was only 3 m/sec, during the afternoon storm period wind speeds at this tower were roughly half that of Keeler and Olancha, and a large dust storm on the lake bed occurred. Conversely, on March 11, wind speeds at the Geomet tower were twice that of Keeler and Olancha. This clearly shows the added complexity to analysis of historical data. Knowledge of the hourly or daily wind speed on a shoreline station and the state of the crust on the lake bed (i.e. blowable, not blowable) is not sufficient to determine the relative strength (or in some cases even the presence) of a dust storm.

Time lapse photography in this study showed dust plumes being entrained as high as 2 kilometers over the lake bed in as little as 5 kilometers horizontal distance. Other studies have observed plume rises twice as large (St. Amand *et al.*, 1986). During the study period air stability varied greatly, with plume rise at angles varying from 10 to 45 degrees. The majority of the daylight periods showed plumes reaching a maximum height over the lake bed of approximately 900 m on the Northeast Sand Sheet. Additionally, morning photos of the plume have shown that it can stay as near to the ground as 100 m. If we assume that even more stable atmospheric conditions exist during twilight and nighttime periods, then the plume thickness probably minimizes to below 75 m.

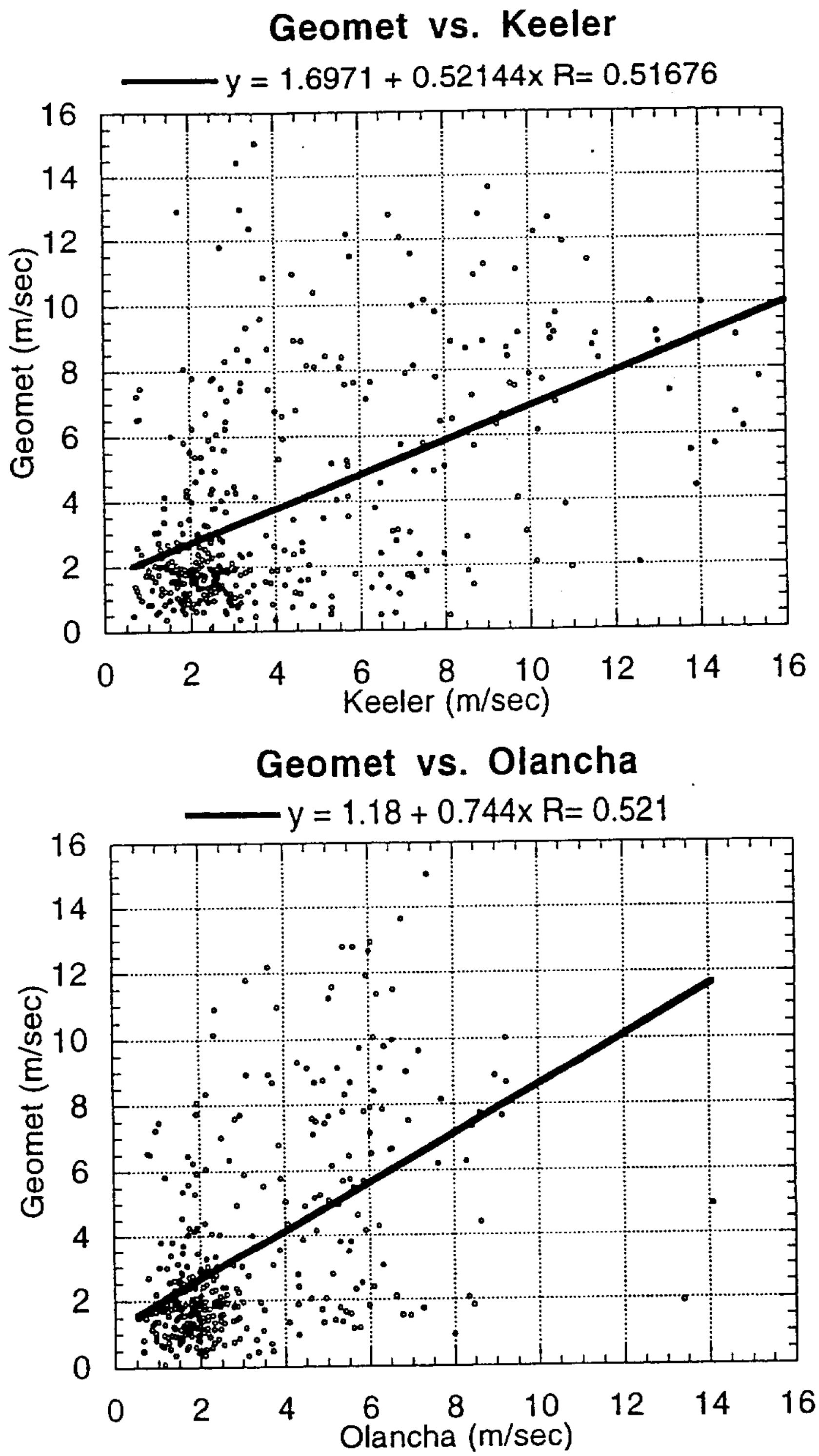


Figure 38. Intercomparison of hourly averaged wind speeds between Geomet site, Keeler and Olancha, March 1993.

Plume rise on the lake bed varied greatly. Plume rise associated with northerly winds generally was limited to 25 degrees while the plume was over the lake bed. This is probably due to the lower roughness height (approximately 0.1 cm) over the 15 km upwind fetch. Plume rise was observed to be much more significant when dust plumes passed over the shoreline into the desert regions (roughness height approximately 5-10 cm). The plume then tended to mark the transition layer started at the shoreline.

The steep walls of the valley, and its variable width (varying by over 30% in this region) partially explain the large surface eddies (~5-9 km in diameter) that occasionally form on and near the lake bed. Meteorological data and the authors' personal observations, as well as observations of local residents, indicated that strong winds can exist on one side of the 28 kilometer wide valley and almost no wind, or even a 180 degree vector reversal of wind direction on the other.

Some of the largest eddies formed along with an increase in the plume rise rates of the dust clouds. This is probably because under unstable conditions, anabatic winds are much more likely to form, adding a cross valley wind vector to the flow. Under the most extreme instability (for example November 27, 1991), these winds can affect the wind field substantially in such a narrow valley .

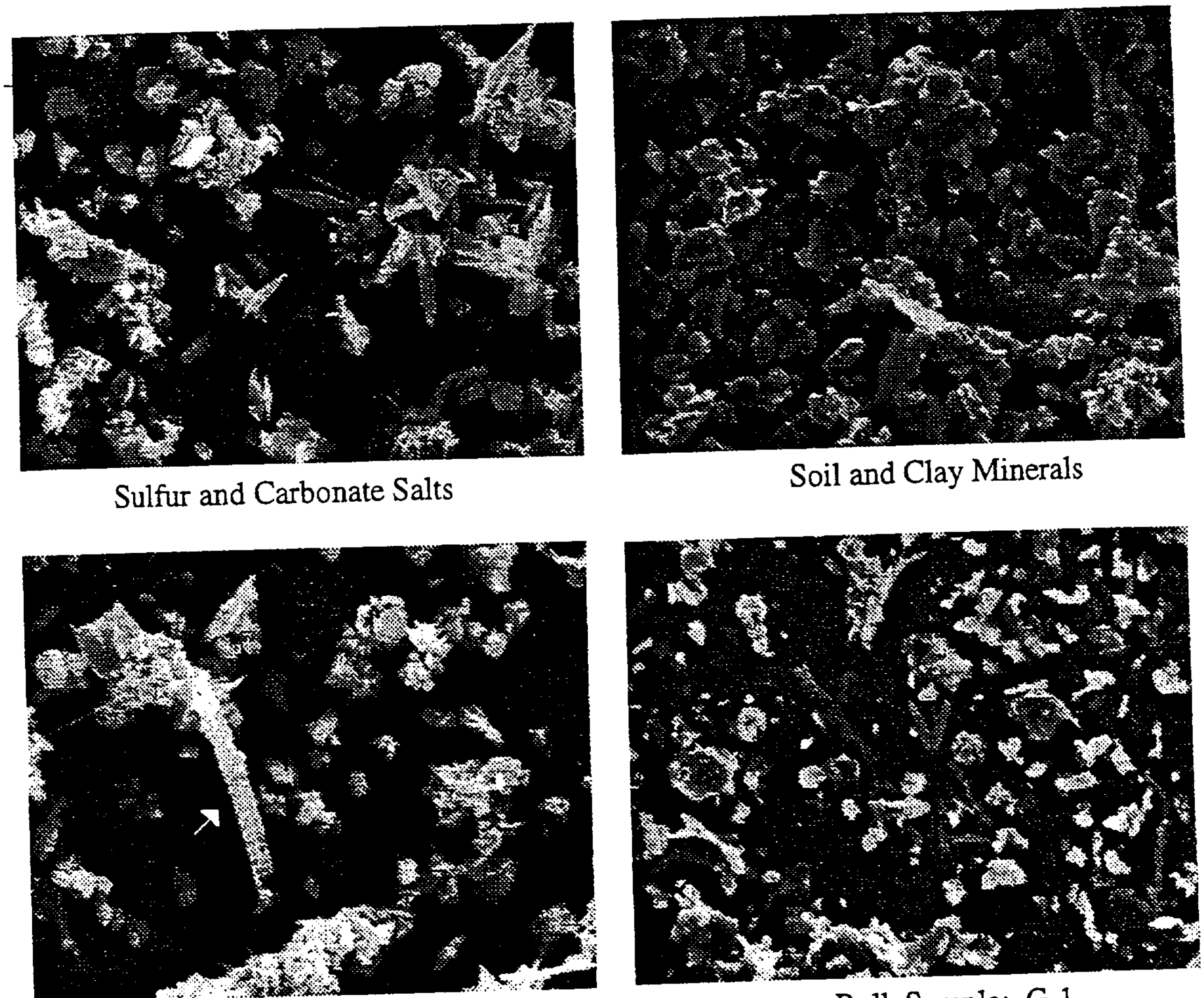
Aerosol characterization

The chemical constituents of Owens (Dry) Lake dusts can vary dramatically by season and production location. Variations in ground water depth, precipitation, ambient temperature and humidity over the weeks preceding a dust event govern the presence and molecular composition of salt crusts. Furthermore, even the existence of a salt crust during a particular dust event is in question. In the spring and early summer, the wide variations in these independent variables makes prediction of elemental makeup difficult and significant variations are observed. The hot days and little precipitation of summer standardize the crust/soil composition and allow for easier predictions during the summer and fall.

Owens dusts have been classified into four categories (Barone *et al.*, 1979; WESTEC, 1984; St. Amand *et al.*, 1986):

1. Soluble salts (halite, thenardite etc.).
2. Carbonates (calcium carbonate, trona etc.).
3. Semi-soluble clays (montmorillonites).
4. Other non-soluble minerals (primary silicate minerals: feldspars, quartz, amorphous silica etc.).

We collected samples that were enriched in each type of dust, as shown by compositional analyses. Electron micrographs of each are presented in Figure 39.



Sulfur and Carbonate Salts

Soil and Clay Minerals

Silicates
(Si-Ca Feldspar? Center)

Bulk Sample: G-1
December 19, 1991

10 μm

Figure 39. Owens (Dry) Lake Dust Aerosol Morphology.

Elemental mass concentrations from PIXE of sampled aerosols generated from the South Sand Sheet are presented in Table XIII, along with data collected in the fall from the north end for comparison. Furthermore, dust storm data collected by St. Amand *et al.* (1986) in the spring of 1976 from aerosols generated simultaneously from the Northeast and South Sand Sheets is presented. These data demonstrate the striking differences in elemental composition of aerosols generated in differing locations. From our spring data we see that the aerosols from the South Sand Sheet are predominantly in the form of sulfur salts (over 60% by mass), and there is an overall lack of chlorine. This was confirmed by energy dispersive x-ray analysis (EDAX). Conversely, dusts generated from the Northeast Sand Sheet tended to be soil dominated with moderate levels of chlorine.

Element	Background Averages	High Mass Non-Storm Period	South Sand Sheet (Spring 1993)	Northeast Sand Sheet (Fall 1991)	South + Northeast (Spring 1976)
Na	6.94	ND	41.40	11.65	36.34
Al	2.13	2.31	5.19	9.55	10.22
Si	49.97	0.26	19.09	35.56	23.52
S	1.5	24.41	18.90	2.84	6.00
Cl	0.55	0.07	0.42	10.01	6.16
K	0.78	0.39	3.50	7.62	4.87
Ca	2.77	3.35	7.63	15.48	5.52
Ti	7.65	11.39	0.68	0.42	0.55
V	0.23	0.68	0.19	ND	ND
Cr	0.03	ND	0.02	ND	ND
Mn	0.07	0.10	0.17	0.16	0.49
Fe	2.70	4.75	2.64	6.38	6.33
Cu	ND	ND	0.06	0.03	ND
Zn	0.03	0.10	0.04	0.07	ND
Hg	ND	ND	0.05	ND	ND
As	ND	ND	0.01	0.07	ND
Sr	0.07	0.10	ND	0.13	ND
Pb	0.03	0.03	0.01	0.03	ND

Table XIII Elemental Composition of Owens (Dry) Lake dust detected by PIXE, selected elements, as % of total mass of detectable elements (Na and heavier). "ND" indicates that element was not detected above the minimum detectable level. Background averages and Northeast Sand Sheet data were compiled from samples taken during fall dust storms. Data from spring 1976 are from St. Amand *et al.* (1986) and include dust generated from both the Northeast and South Sand Sheets. Though elemental data were not taken for one dust event on the Northeast Sand Sheet, St. Amand *et al.* (1986) indicate little seasonal variation in composition.

While we were unable to perform elemental analysis of a source sample of the single observed dust storm of the Northeast Sand Sheet during the spring intensive, the SMART sampler located outside Schulman Grove received appreciable loading. Elemental analysis of this sample supports this claim.

X-ray diffraction of the crust performed by St. Amand *et al.* (1986) and Cochran *et al.* (1988) suggest these salts are probably in the form of thenardite (Na_2SO_4) and its hydrated form mirabilite ($Na_2SO_4 \cdot 10H_2O$). Sodium stoichiometry suggests a high fraction of carbonate compounds such as trona ($Na_3H(CO_3)_2 \cdot 2H_2O$). Electron microscopy of the aerosol samples suggest that 70% of the total mass in the spring events was in the form of soluble salt crystals.

Also of note are the trace metals found in the dusts. Soil surveys conducted by UC Davis (Kusko and Cahill, 1984) have found a mean lake bed arsenic concentration of 50 ppm, while further studies conducted by the GBUAPCD (Hardebeck, 1992) also showed local arsenic concentration maxima in the northern and eastern region above 150 ppm in 1989. Analysis of the thick salt deposits in the center of the playa found levels of arsenic ranging from 12-33 ppm (McClung, 1994). Thus, since the surrounding desert regions have a lower arsenic content than the lake dusts, arsenic is a prime candidate as a natural tracer for the north end of the lake bed.

Aerosol samples taken in the present study showed PM_{10} arsenic levels as high as 464 ng/m^3 when the center of the plume passed through Keeler. Because of the complex chemistry of the crusts, we were not able to adequately determine the oxidation states of the arsenic compounds. The aerodynamic mass size distribution of arsenic showed a maximum at 3 μm, in close agreement with our work during the WESTEC study when we found the arsenic maximum between 2 and 5 μm diameter. Though these sizes were an order of magnitude greater than the typical accumulation mode maximum at 0.3 μm, particles in this size range can be carried long distances in strong winds and turbulent conditions. Aerosol samples taken at G-1 station at NAWS, CL (100 km downwind) showed arsenic levels at 300 ng/m^3. A rough estimate of the total arsenic production for one of the fall storms observed (November 28, 1991) may be given for the lake bed by assessing the plume width and height from time lapse photographs. When the atmosphere was unstable in the afternoon, the dust plume was approximately 450 m high by 5500 m wide. Spatially integrating the DRUM arsenic data from the center to the edge of the plume, assuming a mirror image of species on the other side of the plume, and using a mean wind speed of 12 m/sec over the lake bed, approximately 400 kg of arsenic was produced over a twenty-four hour period. Extending this to the 120 hours of known dust production on Owens (Dry) Lake, approximately 2 metric tons of elemental arsenic was released during the 5 days of the fall 1991 intensive study period. After noting that arsenic-bearing deposits were found on the eastern dust-producing region south of the sampling site, it can be assumed that this arsenic production estimate is a lower bound.

Normalized particulate mass size distributions from the DRUM sampler for Si, S, Ca and Fe in the aerodynamic size range of 0.07 through 15 μm for the March 1993 storm periods are shown in Figure 40a. These data were collected from aerosols generated from the South Sand Sheet. For comparison, size distributions taken in Keeler in fall 1991 from aerosols from the Northeast Sand Sheet are shown in Figure 40b. Due to the extremely low levels of S detected, the much more dominant Cl is presented instead. Concentrations for each given element were normalized to that species total mass value. There is a clear mode in stage 3 (2.5-5.0 μm) for almost all of the species shown, except for Cl. This mode is common to airborne soils generated by saltation (Patterson and Gillette, 1977). Saltation is the accepted process by which clay minerals are "sandblasted" away from the sand particles they are attached to (Gillette and Walker, 1977). Note, however, that this mode is absent in aerosols from typical California agricultural soils in dry conditions (Cahill *et al*, 1984) which typically have maximum masses in the 10 to 20 μm region..

The size distributions for elements typical of soils (Si, Ca and Fe) compared well for the differing time periods and location, showing that the same processes are involved even though the particles are finer than average soils. There were minor differences in size distributions from storm to storm and location to location. The aerosols from the South Sand Sheet have less mass in the submicron range, perhaps due to separation from saltation in the dune fields on the northeastern shore of the lake bed (Reid *et al* , 1993). The increase for stage 1 (10-15 μm) represents a portion of a mechanical mode that probably extends to greater than 20 μm. An increase in the finer modes for the spring events was possibly due to increased production efficiency on the softer soil of the South Sand Sheet.

There is a strong difference between the Cl and S size distributions. Most dramatically, there is a clear absence of the mechanical mode for sulfur, and an absence of a saltation mode for chlorine. However, we know from this and previous studies (St. Amand *et al.*, 1987) that the soft powdery crusts tend to be sulfur dominated. Conversely, the hard erosion-resistant crusts tend to be chlorine dominated. Thus, dissimilarities in the element's size distribution are probably due to differences in the molecular structure, bond strengths, and crystal size.

The bulk size distributions for Owens (Dry) Lake dusts were determined by both aerodynamic means and by mass reconstruction from the DRUM sampler. The size distributions generated in this study are presented in Figure 41. The distributions from the South Sand Sheet (sulfur salt dominated) are presented, as well as data taken from the single spring event from the Northeast Sand Sheet. We see a fair comparison of the size distribution for aerosols from the South Sand Sheet to that of sulfur using data from the DRUM sampler. Modes appear in the same location. Above 8 μm, however, the non-Stokesian flows coupled with the unusual morphologies of the salts caused errors in the APS 3300. However, since we see from the elemental analysis that the majority of these aerosols occur in the form of sulfur salts, comparatively there was much less mass above 6 μm, reducing the potential overall error.

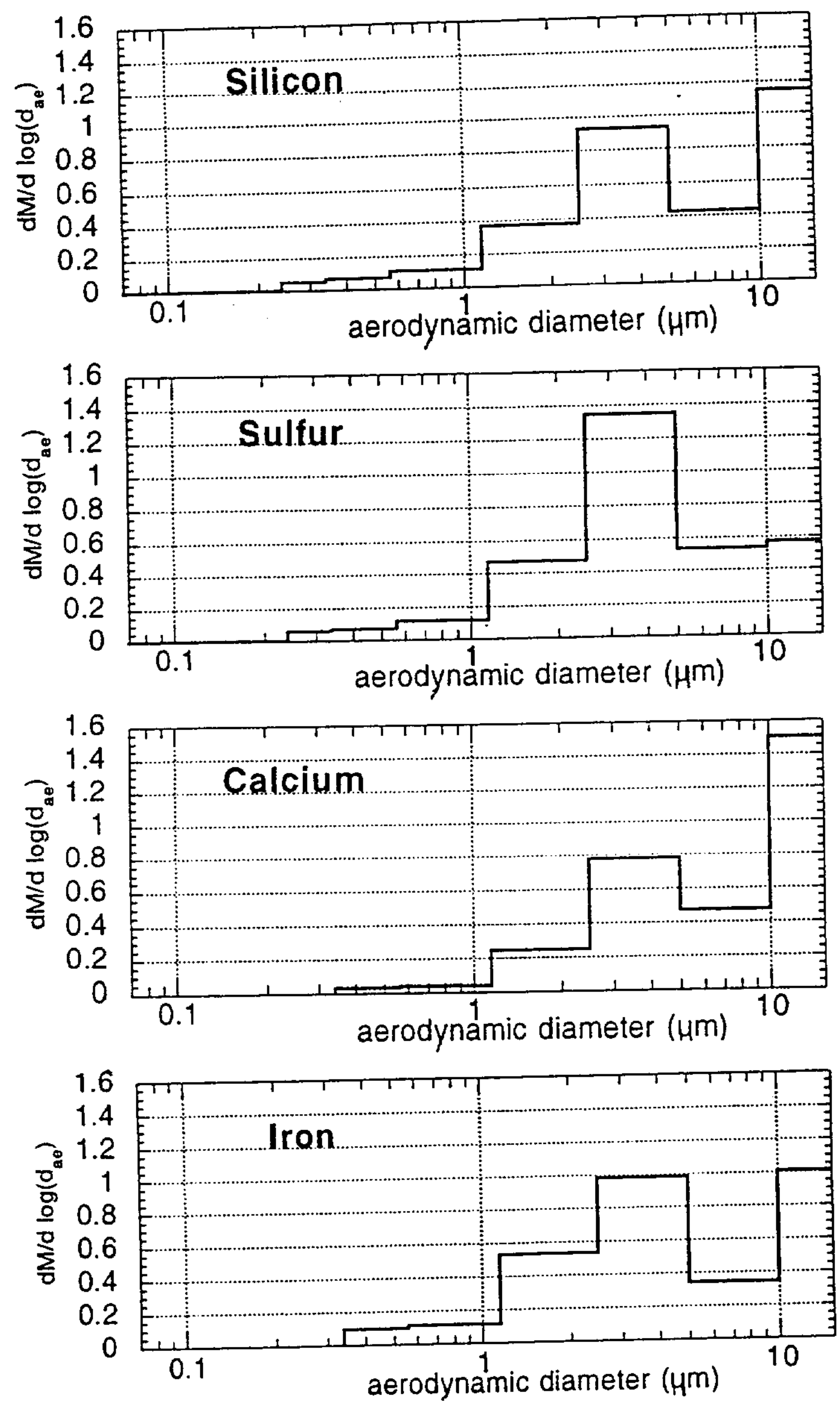


Figure 40a. Normalized size distributions from DRUM sampler, Owens (Dry) Lake aerosols, for four elements, Spring 1993.

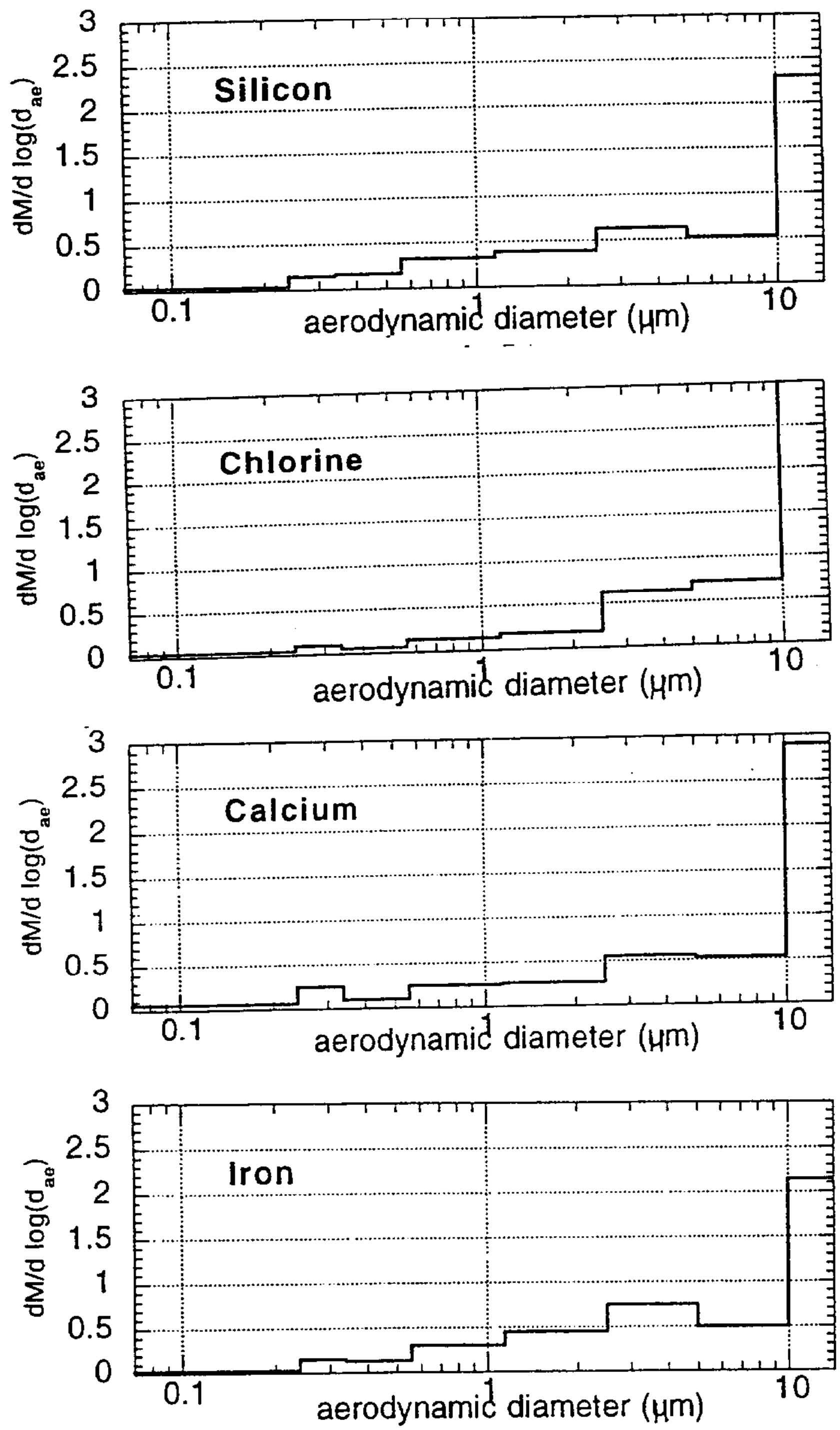


Figure 40b. Normalized size distributions from DRUM sampler, Owens (Dry) Lake aerosols, for four elements, Fall 1991.

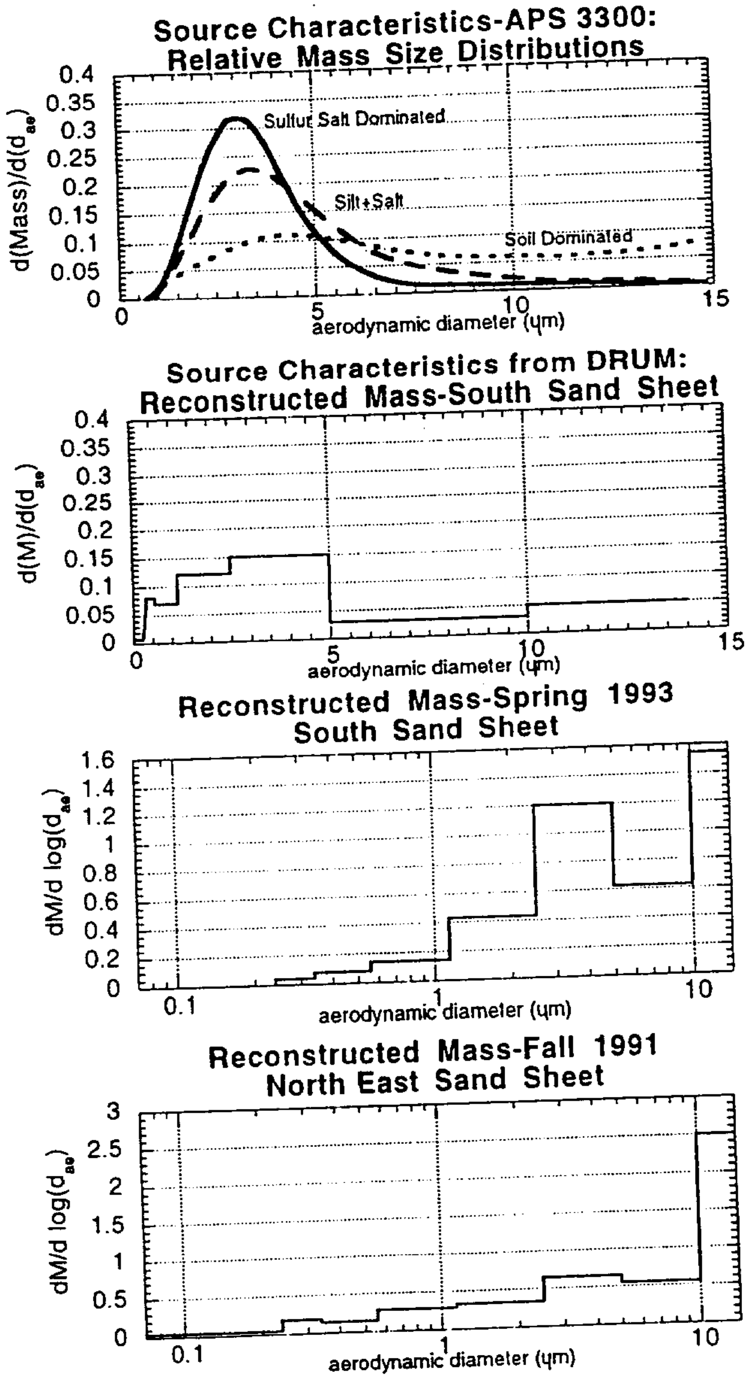


Figure 41. Mass size distributions for Owens (Dry) Lake dust aerosols, March 1993.

While we were not able to collect elemental DRUM data for the single episode of March 24 on the Northeast Sand Sheet, the APS 3300 showed a clear change in morphology. Comparing the size distribution to major elements from the DRUM sampler, we can predict that the majority of this mass was probably soils and chlorine salts, as inferred from St. Amand *et al.* (1986) and the fall data. From these and previous studies on the aerosols and playa surface materials, we can make the following preliminary generalization: Sulfur salts dominate the south, chlorides dominate the southeast, and silicates and soil minerals dominate the Northeast Sand Sheet. Full confirmation of this generalization, however, will require detailed, longer-term geological and geochemical surveys well beyond the scope of this project.

Optical characterization of aerosols

Because of the large areas which are impacted by Owens (Dry) Lake dust plumes and the general lack of infrastructure over these areas, it was useful to develop optical properties/aerodynamic properties/mass relationships so that remote sensing techniques (Satellite, Automatic Cameras, LIDAR etc.) may be employed. This relation aided in developing a mass/optical extinction function to assess visibility degradation in the numerous Class I areas and government installations in the region as well as plume impact in the many small towns in the region without sufficient monitoring. Furthermore, this function can then be applied to determine the end results of mitigation efforts.

We derived a fine particle scattering (0.11-6.0 μm D_{ae}) component from data generated by the laser aerosol counter (LAC). This can then be compared to integrating nephelometer measurements to determine the overall fine particle and TSP contributions to optical atmospheric extinction. Finally, semi-quantitative true visibility estimations were made by camera and technician observation to determine coarse particle and path radiance contributions to visibility degradation. Because of the irregular morphology of the Owens (Dry) Lake dusts, a true theoretical estimation of particle scattering characteristics from SEM and elemental analysis is difficult and was beyond the scope of this study.

We first compared the size distribution of optically equivalent and aerodynamically equivalent diameters for aerosols in the 1-6 μm range (Figure 42). It was evident that the dust's irregular morphology smooths out the optical distribution in comparison to the aerodynamic distribution. If we assumed that the particles have a low complex index of refraction, then overall we estimated $b_{extinction} = b_{scat}$. We next determined an LAC estimated scattering contribution to visibility and compare to the integrating nephelometer. The ratio of LAC scattering to integrating nephelometer scattering was then calculated to determine the contribution by fine particles.

We related the LAC derived visibility to the integrating nephelometer's given visibility in Figure 42. Overall, there was a fair relationship between the devices. Moderate variation in the data points during the poorest visibility (near the source) demonstrated the importance of scattering of particles larger than 6 μm D_{ae}. The large forward scattering components for particles larger than 6 μm, in conjunction with truncation errors by the integrating nephelometer, further confused the issue. While the integrating nephelometer was reading a visibility of 2 km, true visibility was below 500 m. Thus, in cases near the shoreline, visibility was dominated by large particles in the mechanical mode.

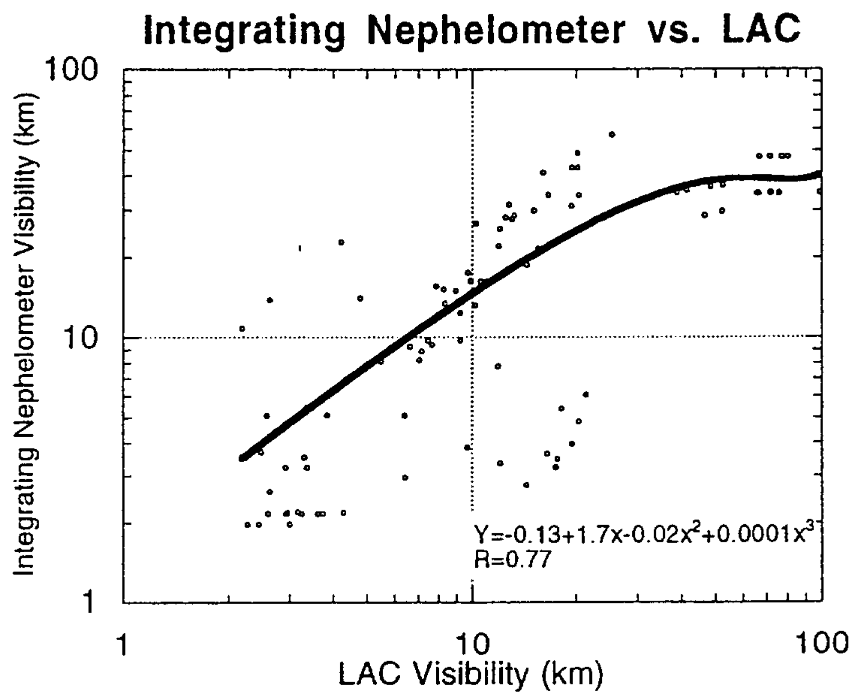


Figure 42. Comparison of visibility derived from integrating nephelometer and laser aerosol counter, Owens Lake region, March 1993.

This made visibility-based PM_{10} estimates unreliable: Figure 43 indicates that the relationship between ambient mass and visibility during March 1993 events would have an r^2 of less than 0.5. Estimation of PM_{10} from visibility by methods such as automatic cameras and external photometry near the shoreline would be extremely difficult. However, if an internal scattering device was to be used (i.e., nephelometers) with appropriate inlet size restriction, then mass estimates from scattering would be more reasonable. Even so, variations in aerosol morphology as discussed earlier requires significantly more research before such scattering/mass relationships can be employed.

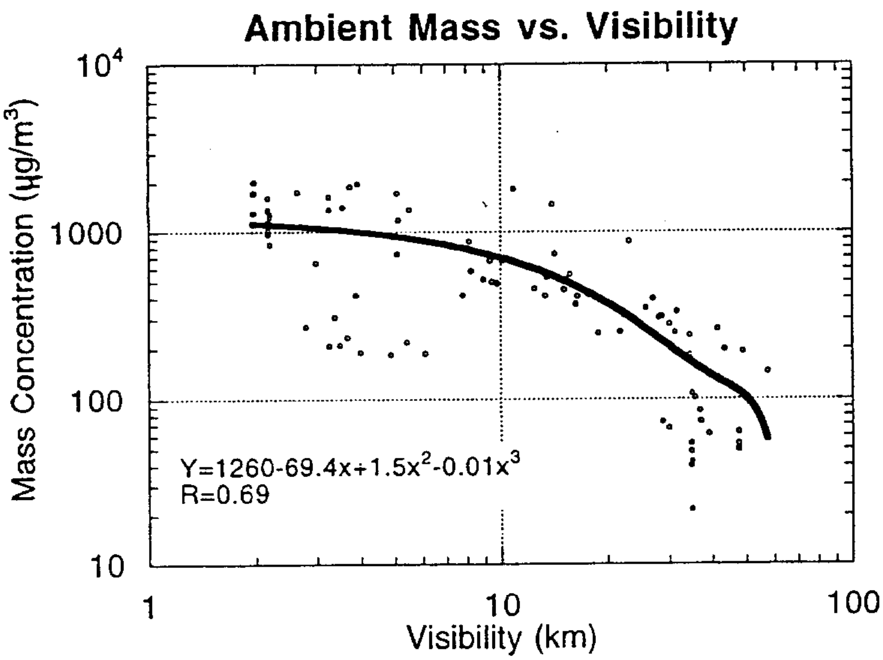


Figure 43. Relation of ambient aerosol mass concentration to visibility, Owens Lake region, March 1993.

The optical/mass characteristics of the dust are exceedingly complex. Figure 44 demonstrates the comparison of scattering cross section and d_{ae} mass estimation by size for an example period. As can be seen, the smaller particles have a significantly disproportionate impact on visibility. Furthermore, the optical mass distribution is smoother than the true aerodynamic mass distribution. Thus, particles in the saltation mode greatly vary optically. This is to be expected from the particle morphology displayed by SEM in Figure 39.

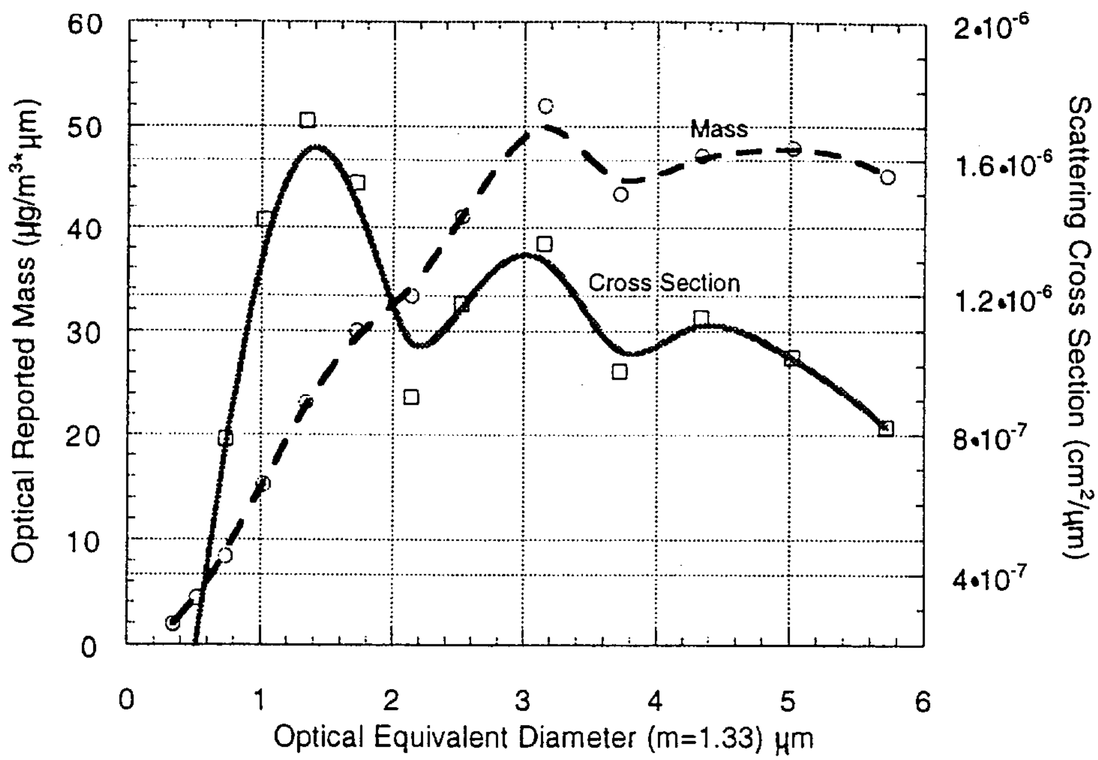


Figure 44. Optical Characteristics of Source Dusts: Example from South Sand Sheet d_{0e} Derived Mass and Related Cross Section.

Aerosol transport

1. Plume Dissipation (dilution + dry deposition/scavenging)

Assuming particles generated at Owens (Dry) Lake into the accumulation mode have very low deposition velocities, and that their concentration is well above background, then concentration measurements of these particles will yield plume dilution. A plot of plume dilution vs. distance is presented in Figure 45. The steep walls of the Sierra Nevada, White-Inyo, and Coso Ranges tend to keep horizontal plume dispersion minimal. The plume width inside the Owens Valley generally varies as function of time of day: the added turbulence of late afternoon storms increases both vertical and horizontal diffusion. Automatic camera data demonstrated afternoon plume rise to over 2 kilometers above the surface. Under these circumstances the plume can engulf the entire valley. Conversely, the stable atmosphere and low planetary boundary layer of night and mid-morning limits such plume dilution.

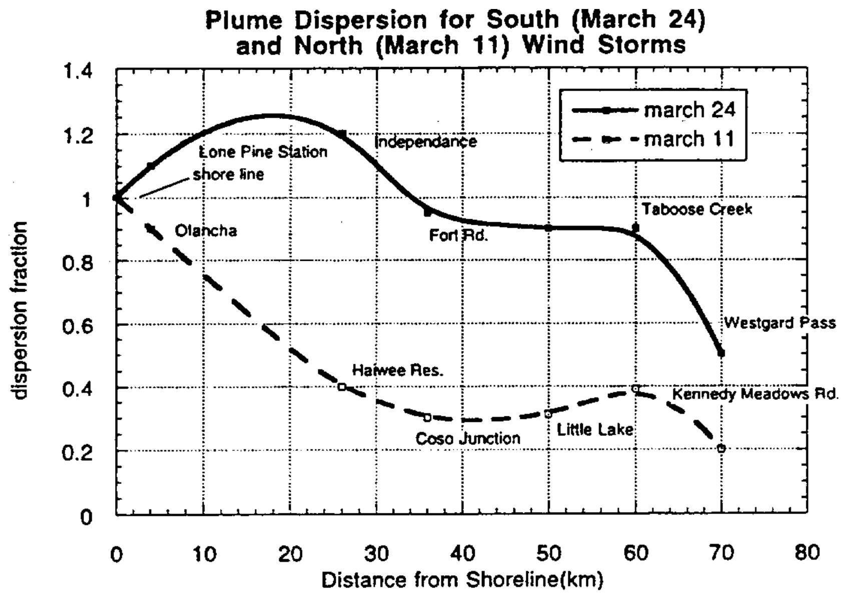


Figure 45. Relation of Owens dust plume dilution to distance downwind, March 1993.

Once the plume of dust is transported into the Panamint, Rose, or Indian Wells Valleys, substantial plume dilution can take place, leading to dissipation. Until such a change in topography occurs, mass concentration can be reduced only by vertical diffusion and dry deposition. Since vertical diffusion subsides when the plume reaches the planetary boundary layer (which occurs with the first 10 km), the only plume reduction method is dry deposition. Thus, plume concentrations can stay at high levels during transport.

Over 100 size distribution data sets were taken during the study to estimate dry deposition velocities. Particle half distances ranged from 35 to 65 km, depending on wind speed. This corresponds to deposition velocities around 10 to 30 cm/sec. Overall, estimated deposition rates are about a factor of 3 to 5 higher than theory predicts. However, current theory is not particularly effective for predicting deposition rates under such adverse meteorological conditions.

a. Northerly Wind

Dusts from periods of all 4 major dust episodes in the fall 1991 study were detected by integrating nephelometers at NAWS, CL. Figure 46 shows estimated aerosol concentrations for Keeler, Baker, and G-1 during the storm period of November 30. Estimates from Baker and G-1 were generated using integrating nephelometer b_{scat} values in conjunction with correlation graphs produced by St. Amand *et al.* (1986). Figure 47 shows most probable transport patterns into Indian Wells Valley. These were computed using meteorological data compiled from Owens and NAWS, CL meteorological stations and using the Sierra Nevada, White-Inyo, and Argus Ranges as boundaries.

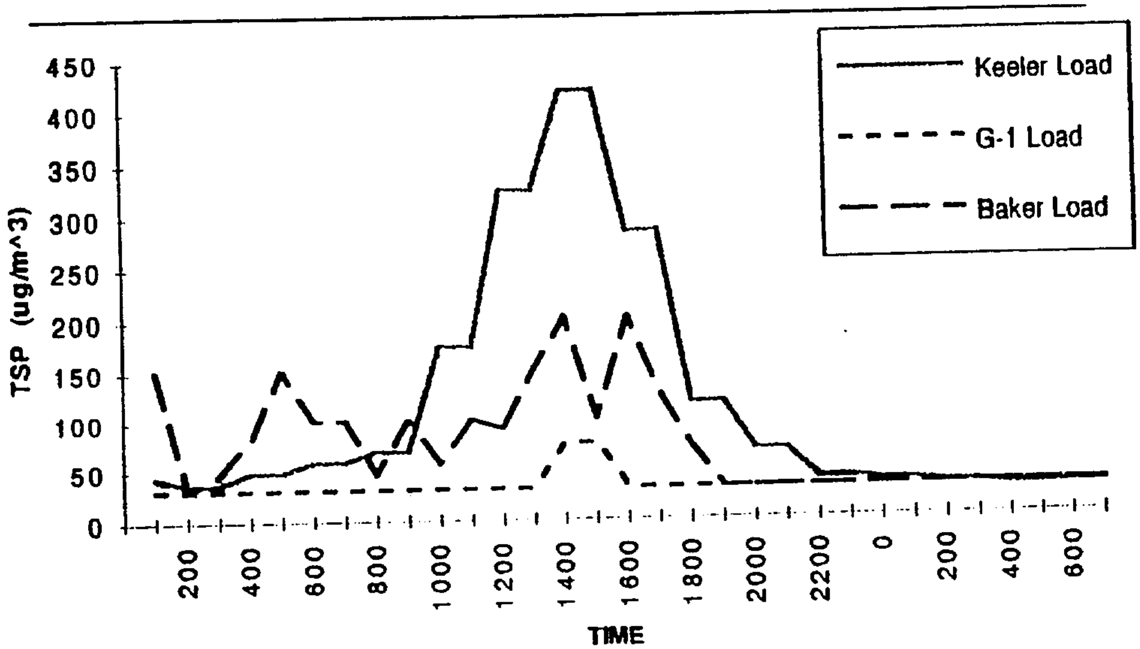


Figure 46. Estimated TSP profiles from Owens dust transported on north wind, November 30, 1991.

Though dust was being generated at a moderate rate on both the north and south ends of the lake bed during the periods observed, the estimated TSP values at Baker and G-1 were sporadic throughout the study period. This reflects the high variability of transport paths. Because of the topography of the region, south-moving plumes have a tendency toward relatively small widths until they empty into Indian Wells Valley. Time lapse photography and data from meteorological stations appear to indicate that dust transport paths are partially dependent on atmospheric turbulence processes. For dusts generated in the north end of the lake bed while the atmosphere is relatively stable with a low boundary layer, the tendency was to be orographically forced to the eastern side of the Coso Range toward the town of Darwin. At Darwin, the plume direction is dependent on winds on the eastern side of the White-Inyo Range. If these winds have strong northerly components, the plume will move south between the Argus and Coso Ranges and eventually empty into Indian Wells Valley, almost directly onto the G-1 sampling site. If the wind does not have a strong northerly component, the plume has a tendency to empty into Panamint Valley. On days of extreme turbulence and a high boundary layer (11/27/91 for example) aerosols are entrained to very high altitudes (above 2 kilometers) and can be transported without topographic forcing directly over the Coso Range. For the south end of the lake bed, it has long been known that the south moving plumes follow the topography of the Sierra Nevada (Cox, 1991). These plumes then simply empty out into Indian Wells Valley, and can either disperse or continue to follow the Sierra Nevada south.

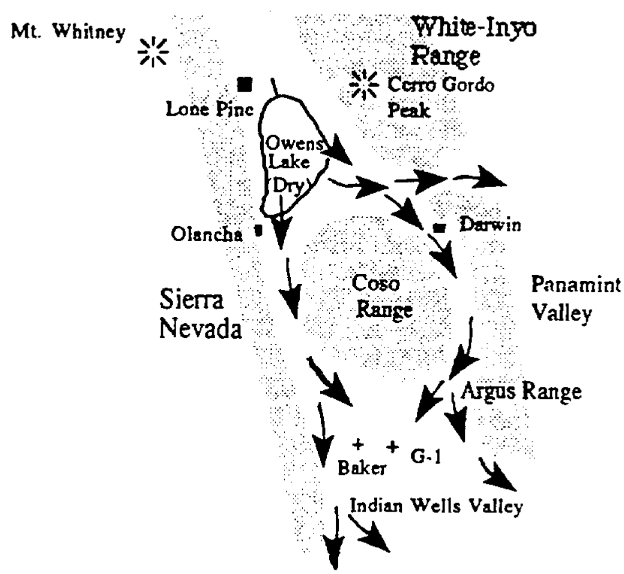


Figure 47. Probable dust transport patterns from Owens (Dry) Lake to Indian Wells Valley.

During the spring 1993 intensive, Owens (Dry) Lake dust was only detected at NAWS, CL for 15 minutes on March 11, the only significant storm during the study period with a strong north wind. Since this storm occurred in the morning, horizontal diffusion was low, keeping the plume fairly narrow even at 100 km downwind.

The meteorology is very complex for dust enents associated with the northerly and the more rare westerly wind storms. The rapid changes in topography produce complicated wind fields in the region. An easterly or northerly wind can exist in the Owens Valley concurrently with a southerly wind in the Panamint Valley. Under most circumstances, dust plumes associated with these storms will be bounded by the local topography. Generally during non-late afternoon periods, plumes which enter Centennial Wash are forced to follow the topography along the Argus Range into Indian Wells Valley and the NAWS, CL or into Panamint Valley. Plumes which reach NAWS, CL are usually detected by nephelometers at the G-1 station. Because of inadequate meteorological data in this region and the short duration of this study, we cannot estimate the percentage of storms entering each receptor area. But considering the infrequency of plume detection at G-1 and the high frequency of dust plumes which enter Centennial Wash, a fair portion of plumes probably impact Panamint Valley. The frequent small dust events in the late afternoon are often carried by anabatic winds up to the crest of the White-Inyo Range. These small plumes can then follow the crest, eventually crossing it, or empty directly into the Panamint Valley or Saline Valley.

The meteorology of dust events associated with southerly wind storms is less complicated. The slopes of the Sierra Nevada and White-Inyo Ranges tend to keep the majority of the plume inside the Owens Valley. Plumes which remain on the eastern side of the valley were occasionally observed to pass over Westgard Pass toward Deep Springs Valley and have been reported to pass through Mazourka Canyon into Saline Valley (Cox, 1991).

Even within the Owens Valley itself, there are significant variations in meteorology as one moves away from the lake region. In Figure 48 we present the correlation graph with and without time to demonstrate this. Hourly correlations are poor, and can be partially explained by the time lag present during front passage. This is demonstrated by the diagonal lines in the time plot. The many vertical and horizontal lines indicate isolated wind events at the Onion Valley site and Olancha, respectively. In Figure 49 we display the daily average wind speed for the two sites along with a segment of hourly wind information for the March 17 storm in order to further demonstrate this point.

As discussed earlier, plumes from dust events which occur at night through late morning and early afternoon experience little horizontal diffusion and stay close to the mountain ranges. Thus, towns along Highway 395 north of the lake tend to be infrequently impacted. Plumes from events in the middle to late afternoon, however, can experience the diffusion necessary to impact these towns. This is evidenced by Barone, *et al.* (1979). Recorded impact of dust on these towns is significantly less than one would expect by looking at Keeler. Thus, the averaging of the data obscures the true nature of plume transport. It was suggested that the plume diffused significantly by the time it reached Independence and beyond. This probably is not the case. Because of the differences in chemistry of plumes from different locations, local towns may be affected by different portions of the lake bed. This can make the usage of a single natural tracer element unreliable.

The anabatic winds play a significant role in plume transport. Plumes were frequently observed to be pulled up into the Sierra Nevada and White-Inyo Ranges. Furthermore, these same winds keep dust impact on the mountain ranges, and away from the center of the valley. Data from the SMART sampler located outside Schulman Grove (100

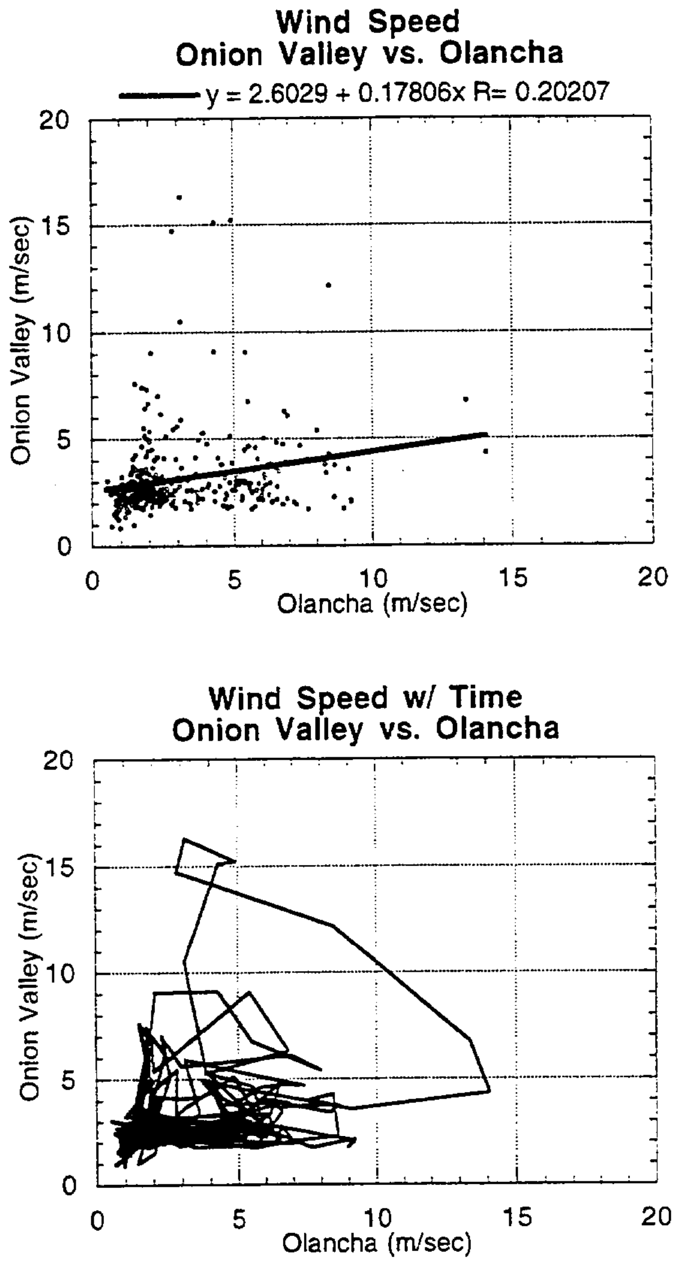


Figure 48. Wind speed correlation, Olancha (near Owens Lake Bed) vs. Onion Valley (east slope Sierra Nevada), March 1993.

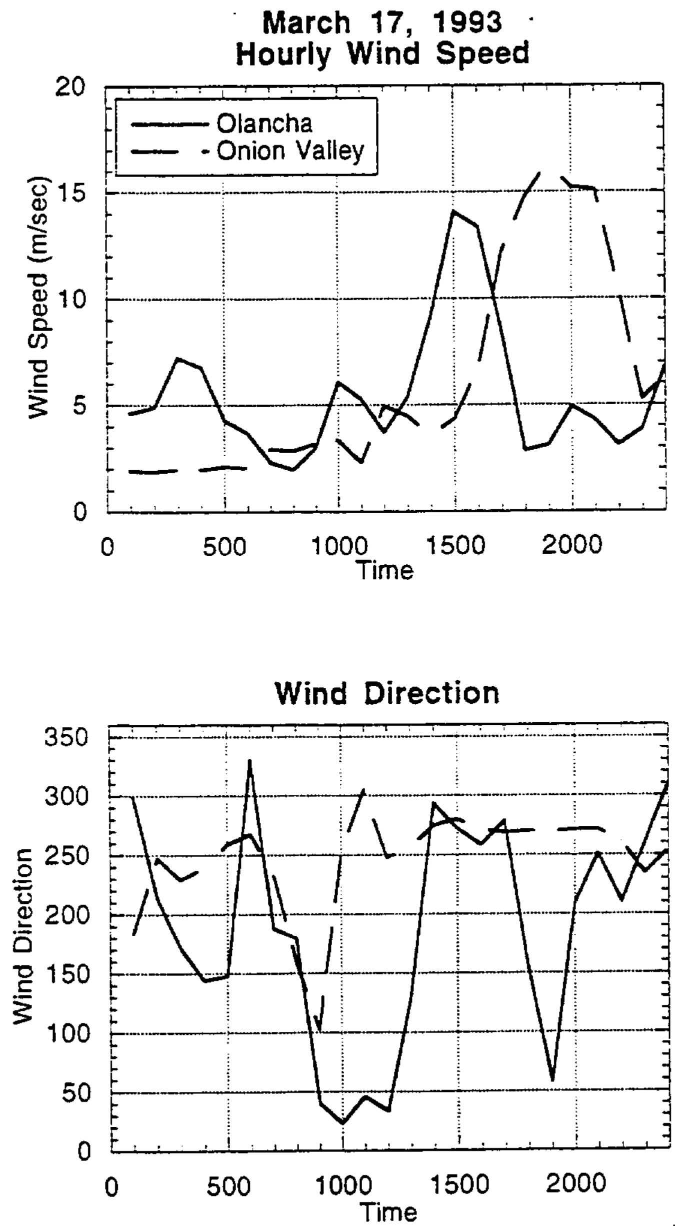


Figure 49. Comparison of hourly wind speed, March 17, 1993, Olancha and Onion Valley.

kilometers downwind) show how the plume can move long distances along the base of the mountain range range (Figure 50). The largest impact was observed on March 24. The investigators in the mobile unit witnessed the impact and noted that there was little visibility impact in the valley at this time, and the plume was completely on the side of the White-Inyo Range.

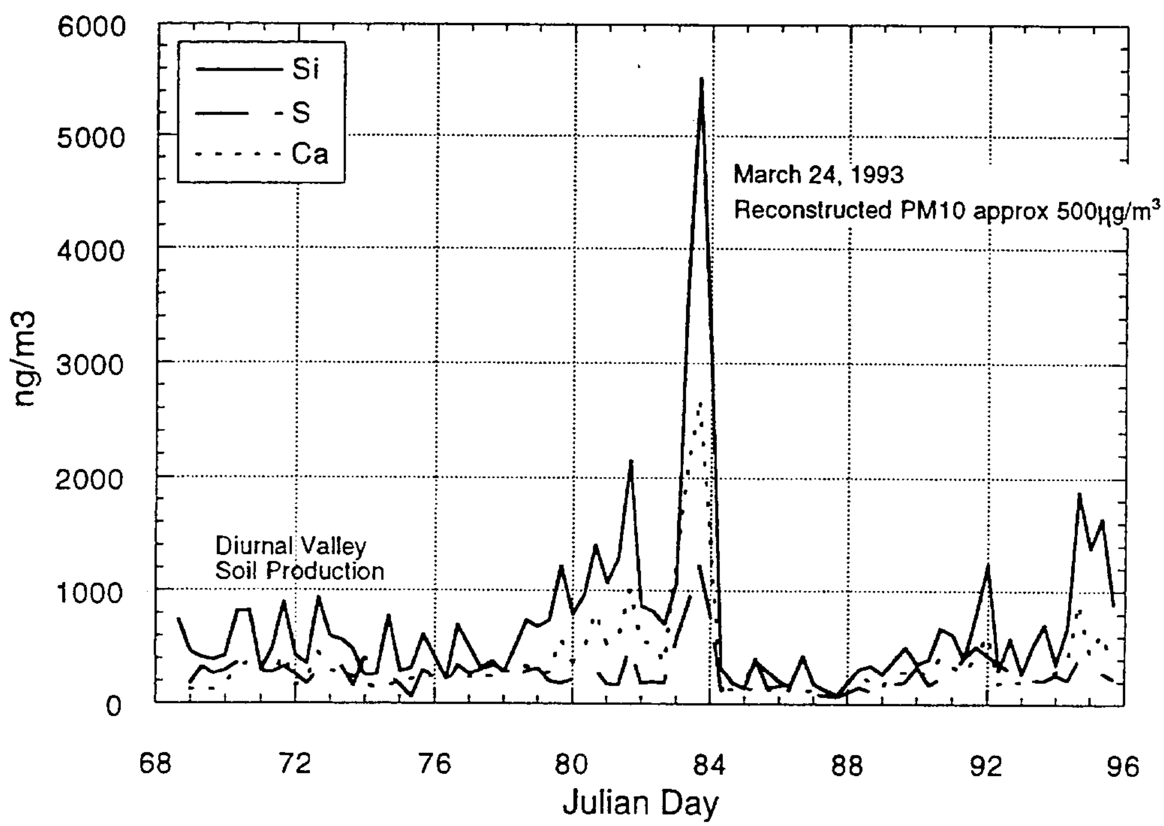


Figure 50. Elemental mass at Schulman Grove, March 1993, SMART Sampler, $PM_{2.5}$, for Si, S and Ca, showing impact of March 24 dust plume

The transport of Owens (Dry) Lake dust into the White-Inyo Range has been observed before (Spear, 1977: reproduced here in Appendix F, and M. De Decker, 1991) and recorded in photographs, but to our knowledge, this is the first measurement of the actual concentration of dust and the characteristic signature (very fine silts; alkaline sulfate salts, etc.) of the Owens Lake playa. However the diurnal transport from the Owens Valley up the west facing slopes mirrors the strong and regular up-slope transport of air pollutants from the San Joaquin Valley onto the western face of the Sierra Nevada, documented in detail at Sequoia National Park during our earlier study for the ARB (Cahill *et al*, 1989). While the efficiency of transport appears low in this case, with the maximum concentration of 500 $\mu g/m^3$ being less than 2% of the near-lake bed value (see below) we have no way to estimate the frequency and severity of such transport over a longer period of time. Nevertheless, it is well known from work in the Tahoe Basin that some mountain trees are salt-intolerant, and thus a certain degree of concern must be maintained regarding the effects of these dusts on the Bristlecone Pine ecosystem. About a third of the total mass of soil in the high altitudes of the White Mountains is derived from material transported into the area by the wind, including dusts generated by the sudden drying of pluvial Owens Lake at the end of the last ice age about 10,000 years ago (Marchand, 1970). The transport of fugitive dust from Owens (Dry) Lake to the same location today appears to be accomplishing a similar process on a smaller scale (Gill, 1994). It is also interesting to note that the growth rates of these very pines are being used to evaluate the effect of increased CO_2 levels on plant growth as part of global climate change studies. A growth reduction due to salt could mask a CO_2 increase. We recommend further research to provide better estimates of the dust transport and its effect on these ancient trees.

Finally, the dust measurements at Keeler are not necessarily the highest values that occur at the edge of the lake bed. We have already commented on the low values for the standard one-day-in-six PM_{10} measurements. In only one case, on March 23, did the center of a dust plume appear to pass directly through the township. The TEOM measured a maximum value of 2003 $\mu g/m^3$ at 5 p.m.. But on March 24, at 3 p.m., the TEOM at Keeler listed loadings at 458 $\mu g/m^3$ while six kilometers downwind we monitored loadings of 27,000 $\mu g/m^3$. Thus, the bulk of the dust produced was not accounted for at Keeler. Similarly during the fall 1991 study, the automatic camera showed the bulk of the dust during the storm periods generally west of Keeler.

With regard to transport and dust impact at receptor locations we must say that this study was conducted over a fairly short period and this could not determine the frequency of impact to many in remote areas in the region. However, all of our observations in this study are consistent with the mesoscale meteorology of the region. We have no reason to believe now that any of the transport phenomena presented here are isolated incidents. The 10 years of PM_{10} data and intermittent studies have only touched on the true nature of the dust events. Twenty four hour sample averaging loses necessary information on instantaneous plume loadings, which are observed to be almost an order of magnitude greater than what is measured in a twenty four hour sample. Furthermore, the plumes of dust events under stable conditions are narrow and can completely miss one sampling site and yet severely impact an area only kilometers away. To obtain better spatial coverage in the region, and especially roadless areas of the region, we must rely on remote sensing.

Remote sensing

Use of the GOES satellite data enormously expands the spatial coverage of the Owens (Dry) Lake dust storms, but suffers from poor temporal coverage and a lack of "ground truth," i.e., how much dust is represented by the observed haziness.

GOES 7 data included the complete dust event on March 11 and partial coverage, due to cloud cover, on March 17 and 24. In all of these events, the GOES data, in conjunction with the SMART sampler, showed significant impact on the Inyo National Forest and its daughter wilderness areas. Furthermore, on March 17 this method successfully detected the substantial plume impact into Panamint Valley (Figure 51) with visibility degradation to 15 km, even though most of the day was obscured by clouds. Only partial coverage was available on the March 24 storm due to significant cloud cover. The March 11 dust storm indicated plume intrusion into the Sierra Nevada and the South Sierra Wilderness area (Figure 52). However, the almost total snow cover significantly reduced sensitivity and the extent of the intrusion is unknown.

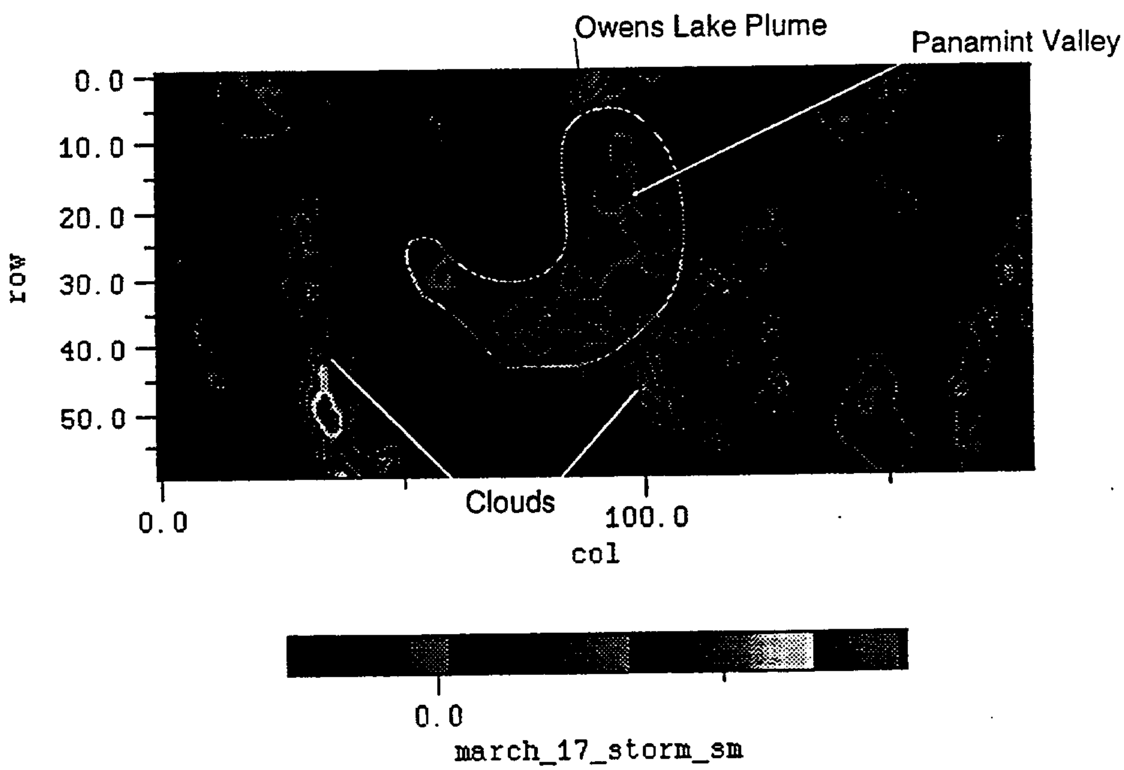


Figure 51. GOES Imagery- Owens (Dry) Lake Dust Storm 16:00 March 17, 1993

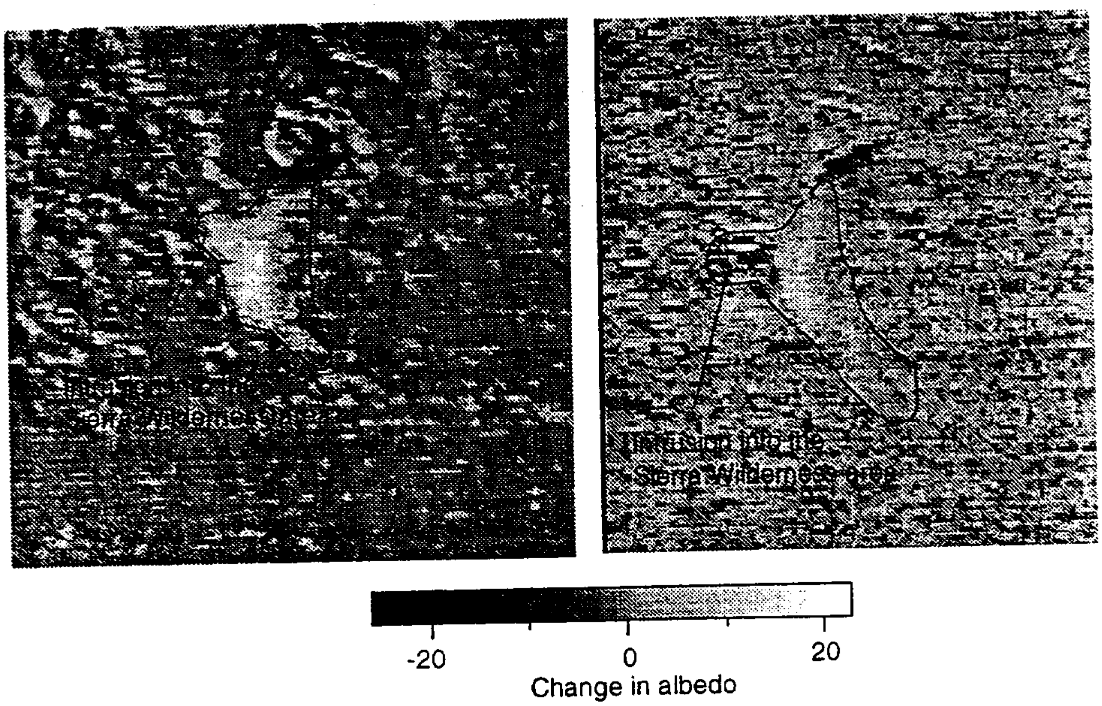


Figure 52. GOES Imagery- Owens (Dry) Lake Dust Storm, March 11, 1993.

Overall, this methodology seems partially feasible if used in conjunction with the appropriate ground truth. Full optical characterization of the aerosols is necessary before such work can be done.

CONCLUSIONS OF THE OWENS LAKE DUST STUDIES

This project has greatly expanded our knowledge of the details of Owens (Dry) Lake dust storms, particularly by the continuous presence of our personnel on the lake bed even during several severe storms. Hundreds of hours were spent on the lake bed in the storms of March 1993. The phenomena associated with dust generation were observed first hand at close range. For instance, the demarcation between the efflorescent salt crust and the broken beige salt-sand mixture steadily migrated through the fetch effect test array between March 11 and March 23, while on March 17 and 24, investigators trekked upwind in a plume to the exact point of initiation of a dust event, photographing and measuring the phenomena.

All these studies confirm the earlier work on the importance of abrading sand and large diameter crustal debris in the vast majority of the dust events. Stunning photographs show plumes arising only from the gray-beige regions of degraded surface, while the white salt crust was without visible dust. The lack of moving particles was confirmed by relatively empty BSNE sand traps at the Geomet tower, which remained in the salt crust area for much of the March 1993 episodes.

RESULTS - VEGETATION STUDY

Field Work

Vegetation field work was performed during late summer and fall of 1992 (August 23-26, September 7-11, and November). Perennials were still thriving while the soil conditions were at their most extreme. Soil parameters are subject to change after precipitation during the rainy season. Delayed winter rainfall in 1992, however, justified the late November trip when field work was done at Sulfate Well. At Keeler and Tamarix Spring, vegetation stands were visually defined according to composition, and "dog-leg" (V or W shaped) transects were set up within each stand for plant and soil sampling. Visual estimates of vegetation cover were recorded by species using Daubanmire's quadrat (1 m x 4 m) placed at constant intervals along the transects (the interval, however, varied among stands, depending on the size of the stands.) We used the standard cover classes used by the California Department of Fish and Game (1987) (Table XIV) to classify the proportion of the surface covered by vegetation. The percentage cover of the tall non-native shrub, *Tamarix ramosissima* (Yau, 1993), was determined by the point-center method. The average vegetation height for each species was estimated to the nearest centimeter. Shoreline and spring species are listed in Appendix E.

Code	Class Range (%)	Midpoint (%)
T	0.1 < 1	0.5
P	1 < 5	3
1	5 < 15	10
2	15 < 25	20
3	25 < 35	30
4	35 < 45	40
5	45 < 55	50
6	55 < 65	60
7	65 < 75	70
8	75 < 85	80
9	85 < 95	90
F	95 < 100	97.5

Accuracy Standard =± 1 class

Table XIV. Plant Cover Classes (CA Department of Fish and Game, 1987)

Soil samples were collected every five quadrats using a soil corer with core diameter of 3.8 cm and length of 30 cm. Six cores were collected in a zig-zag pattern within each quadrat to make a composite sample. The cores were subdivided into 3 classes: 0-5 cm, 5-15 cm, and 15-30 cm and were sealed in zip-lock bags. In addition to the dog-leg transects, three gradient transects were established at each site, cutting across major vegetation zones perpendicular to the boundary of the springs. The transects ended at the zone void of vegetation, and therefore each transect had a different length. The sampling method for plants and soil was the same as described above.

As revegetation is a potential mitigation alternative to dust problems at Owens (Dry) Lake, this study investigated the plant-soil relationship of the local alkaline meadow communities around the lake bed. The spring and well sites studied had low species diversity during summer, the time of sampling, but a high species cover, and clear zonation patterns (except at Sulfate Well). Soil at all depth levels was alkaline, while salinity generally decreased with depth. Soils at Sulfate Well were non-saline, probably because of leaching by the standing water. Regression analysis of cations and percentage organic matter indicated that cations were aeolian originated (except at Tamarix Spring). Na^+ was the major cation contributing most to electrical conductivity and appeared to cause the dispersion of soil, especially when water content was low. Overall pH was the major factor governing the community structure at all of the three sites. It also affected the abundance of non-tolerant halophytes. Electrical conductivity (and hence salinity) and moisture, which were likely determined by microtopography, also influenced species distribution and abundance directly (i.e. the zonation pattern and probably plant height) and indirectly (i.e. the pH values).

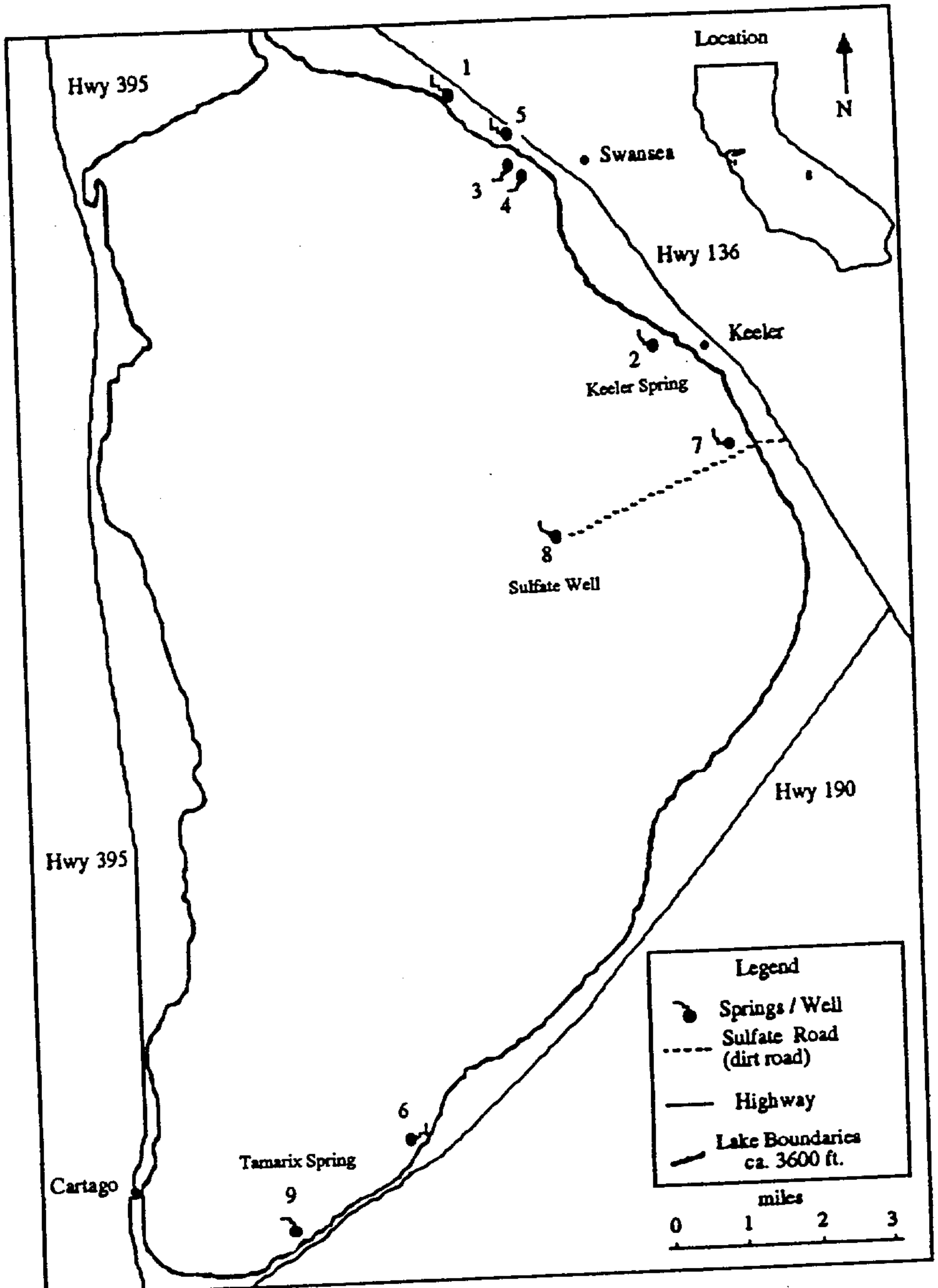


Figure 53. Location of various springs and well sites at Owens (Dry) Lake. Refer to Table XV for the species composition of the sites which the numbers represent (after Yau, 1993).

Spring Name*	Species
1. Spring Volcanoes *	*Anemorphis californica; Atriplex parryi; Atriplex phyllostegia.*
2. Keeler Spring *	*Scirpus robustus; Distichlis spicata; Nitrophilis occidentalis; Scirpus americanus; Polypogon monspeliensis.*
3. Cattail Mound	*Typha spp.; Atriplex phyllostegia; Distichlis spicata; Sesuvium verrocosm; Cleomella obtusifolia.*
4. Greasewood Mound *	*Sarcobatus vermiculatus; Atriplex phyllostegia; Distichlis spicata.*
5. Tamarix Mounds *	*Tamarix ramosissima; Atriplex phyllostegia; Suaeda spp.*
6. Dirty Socks Spring	*Distichlis spicata; Nitrophilis occidentalis; Atriplex parryi; Scirpus robustus; Suaeda spp.*
7. Sulfate Spring *	*Scirpus americanus; Juncus spp., Anemorphis californica.*
8. Sulfate Well	*Scirpus americanus; Distichlis spicata; Nitrophilis occidentalis.*
9. Tamarix Spring *	*Tamarix ramosissima; Atriplex parryl; Distichlis spicata; Nitrophilis occidentalis; Scirpus americanus.*

* names of these springs are not official but given arbitrarily for convenience.

Table XVa. Major species found at various springs on the east side of the lake bed.

Community type	Major Species
Riparian	*Juncus spp., Carex spp., Phragmites spp., Salix spp., Typha domingensis.*
Saltgrass Meadow	*Distichlis spicata, Juncus balticus, Sidalcea covillei, Calocortus excavatus, Astragalus lentiginosus subsp. glomeratus.*
Large Saltbush Scrub	*Atriplex torreyi, A. canescens, A. polycarpa, Chrysothamnus spp.* (sensitive to water withdrawal)
Alkaline Sink	*Allenoflea occidentalis, Suaeda torreyana, Atriplex parryi, Cordylanthus maritimus subsp. canescens, Cressa depressa* (highest tolerance for alkali, but need high water table)
Sagebrush Scrub	*Artemisia tridentata* (requires deep soil and persistent groundwater)
Greasewood Scrub	*Sarcobatus vermiculatus, Tetradymia glabrata,* (most common, reach very deep underground water)
Shadscale Scrub	*Atriplex confertifolia, Ambrosia dumosa, Artemisia spinescens, Ephedra nevadensis.* (depend on surface runoff)

Table XVb. Owens Valley Plant Community Classification (by Mary DeDecker). The communities are arranged in descending order of sensitivity to water withdrawal (Gaines and DeDecker 1982).

Saltgrass (*Distichlis spicata*), *Scirpus robustus*, and Bulrush (*Scirpus americanus*) are potential candidates for revegetation in dune arrays with water releasing points. Salinity, pH, and water depth need to be managed and monitored for proper growth of the species. Further studies need to be done on the ecology of *Nitrophilis occidentalis* and Parry Saltbush (*Atriplex parryi*), especially on their rooting environments. Interaction between species and within the population of the species recommended for mitigation should be investigated. Cautions need to be made so as to minimize the establishment of the exotic, invasive, exclusive, and water-consuming *Tamarix ramosissima*.

If riparian corridors with a dune array and water releasing points (wells) are established, Bulrush (*Scirpus americanus*), and *Scirpus robustus* would be the species most suitable for revegetation around the well and dunes where standing water is available. Bulrush (*Scirpus americanus*), in particular, is able to increase its height upon sand accretion (Seliskar, 1990) making it an ideal species to be established around the dunes. Its roots and rhizomes are also able to extend deeper when the water table is lowered (Seliskar, 1990). As discussed previously, pH has to be maintained at least below 10 for the establishment of these species. *Scirpus robustus* seems able to tolerate relatively higher salinity and might grow better at more saline and alkaline sites.

Able to tolerate wide ranges of pH and salinity, Saltgrass (*Distichlis spicata*) is another candidate for revegetating sites that have no standing water but a high water table. Its tolerance to heavy metals in soils by secretion rather than accumulation is also a favorable feature (Prodgers & Inskeep, 1991). But field studies were done only on acidic-slightly alkaline and sodic soil as well as alkaline but non-saline or sodic soil where Cu^{++}, Zn^{++}, and Mn^{++} dominated. Its tolerance to boron and probably arsenic, which were found in saline sodic soil at Owens (Dry) Lake, should be investigated. Since vegetation height directly affects the friction velocity for the generation of dust storms (Cochran *et al.*, 1988), further studies of saltgrass should be emphasized on its display of dwarfism and the factors (phenotypic/genotypic) governing this response.

This study only investigated soils down to 30 cm deep and thus the rooting environments of shrubs such as Saltbush (*Atriplex parryi*) and tamarisk (*Tamarix ramosissima*) are not known. However, these two species seemed to establish where Na/K at 5-30 cm depth levels was very high, which was likely to exceed even the limit of tolerance of the halophytic perennials. The shrubs probably develop deeper roots, utilize underground water as resources, and therefore, are able to avoid the hypersaline soil environment. Further studies on plant soil relationships need to be done if shrubs are to be established.

Whether plants will be established by seeding or transplanting, seeds or plants grown in ecologically similar areas, i.e. a local source, should be used (McKell, 1986). A greenhouse study (Hensen *et al.*, 1976) showed that Saltgrass (*Distichlis spicata*) maximized its growth in concentrations of salt that generally reflected the salt solution concentrations normally encountered in the field. Populations of a species growing in different environments might have different responses to stresses. For instance, field crops having a higher concentration of Ca^{+2} at the leaves are more sensitive to Ca deficiency (Portor & Lawlor, 1991).

Although heavy grazing might control the establishment of *Tamarix*, it might also affect the growth of native species and thus is not desirable. Repeated intensive grazing of Bulrush (*Scirpus americanus)* by snow geese was found to decrease the quantity of rhizomes (Belanger *et al.*, 1990) and thus the nutrient storage for the plants. Grazing on Saltgrass (*Distichlis spicata),* probably with heavy metals excreted and accumulated on its leaf surface, is hazardous. In addition, grazing on plants growing in contaminated soils is harmful to livestock, which usually consume some soil during grazing (Prodgers and Inskeep, 1991).

This study of vegetation on the Owens Lake playa has highlighted the need for an integrated and ecologically sound solution to dust episodes. This is also the conclusion of Herbert (1965), summarized in Appendix G.

Conclusions of the vegetation studies

A variety of native plants have the ability to survive on the playa, some with a little additional water, and some with only rainfall as a water source. These plants, especially if protected from sandblasting, can assist in the development of vegetated areas on the playa, and help in the long term mitigation of dust events in an ecologically sound manner

SUMMARY AND CONCLUSIONS

In most years, the highest 24-hour PM_{10} readings in California occur downwind of the artificially desiccated Owens and Mono Lakes along the border of the Sierra Nevada and Great Basin. During the LODE intensive study of March 1993, a 24-hour PM_{10} concentration exceeding 2600 $\mu g/m^3$ was recorded by GBUAPCD at Keeler, and we recorded short-term (2 hours or less) PM_{10} levels exceeding 40,000 $\mu g/m^3$ on the South Sand Sheet and 27,000 $\mu g/m^3$ at the edge of the playa. In fact, some of these values are the highest PM_{10} values ever seen in the United States; Owens Lake playa alone has been estimated to produce several percent of the PM_{10} dust in the United States. In addition, aerosols generated from the Owens and Mono playa contain a number of substances that present potential health concern, such as sulfates, selenium, and arsenic.

The nature of these PM_{10} dusts, the mechanisms that dominate their formation, the chemistry and size of the particles, and their transport to receptor areas were first investigated by the UC Davis Air Quality Group in studies funded by the Research Division of the California Air Resources Board from 1978 through 1984. These studies were extended by other groups, including the State Lands Commission (WESTEC, 1984), the Los Angeles Department of Water and Power, and the Great Basin Unified Air Pollution Control District. Additional work was performed by scientists from NOAA in Boulder, Colorado, and the Naval Air Weapons Station at China Lake, while parallel programs at Mono Lake delivered new information relevant to Owens (Dry) Lake. These studies also laid the basis for mitigation efforts at both lakes. But questions still remained regarding detailed source mechanism, transport, and optimum mitigation strategies. This project was designed to address some of these problems.

We performed a sequence of field and laboratory work to determine the conditions that initiate Owens (Dry) Lake dust events, on the physical and chemical nature of Owens dust aerosols, and how they relate to the conditions on the Owens playa itself. We determined the nature of aerosol sources and aerosol generation by extensive analysis of lake bed materials and conditions, extensive aerosol monitoring, and a large set of meteorological data. The project also included aerosol transport and deposition, which we determined using a combination of on-ground data collection at low and high altitudes, and remote sensing techniques including satellite observations and laboratory simulations.

The data gained from this study will be useful for understanding the connection between dust in the atmosphere and local and regional meteorological conditions, the mechanisms and persistence of dust transport, and the physical and chemical characteristics of sediments transported during playa-derived dust storms (with implications for PM_{10} and other pollutant monitoring/estimation). This project made a careful link between aerosol and meteorological measurements near and downwind of the lake bed, which will improve the modeling of playa-generated dust storms in terms of particle flux vs. distance from source.

The tasks were accomplished in four distinct primary study periods:

1. November-December 1991 near Keeler: monitoring of 21 days with 2 hour resolution including 4 dust events, size-compositional aerosol analysis, photographic and meteorological records, playa condition reconnaissance.

2. Spring 1992 - spring 1993: Studies of vegetation patterns, seeds, soil types, etc.; development and testing of instrumentation, intermittent dust production monitoring.

3. March 1993: Spring intensive (LODE), major field experiments, saltation-aerosol connections, fetch effect studies, transport studies.

4. April-June 1993: Sand motion studies, aerosol studies, playa conditions and mitigation evaluation (work in cooperation with ongoing State Lands Commission contract with major GBUAPCD interaction).

In the course of these programs, new types of portable aerosol samplers had to be designed in order to measure PM_{10} in winds up to 40 m/sec (peak gust) and in the presence of massive amounts of blowing sand. With the NOAA instrumentation, the Owens Lake Intensive (the Lake Owens Dust Experiment, LODE) turned out to be one of the most intensive primary aerosol studies ever done. The primary data set includes thousands of sand and aerosol samples, many of which were taken on the lake bed during intense sand/dust storms.

The most important conclusions of the study are as follows:

Source mechanisms for PM_{10} dust generation

a. Sources of Saltating Particles

Saltating particles first arise from loose materials located at the periphery of the Owens Lake Bed, including the Olancha Dunes, silt washed onto the lake bed by ephemeral streams, and the Dirty Socks Springs dunes. They may also arise from friable efflorescent crusts that form in spring, and crust disturbed or broken on the lake bed (including on-road and off-road activities). Following the breakup of the crust itself, fragmented crustal materials become the dominant source of the saltating particles.

b. Mechanisms of Initiating Saltation

It has long been known that in spring, a friable, efflorescent crust develops over much of the lake bed due to brines just below the lake surface. We were able to document the rapid destruction of this crust in a period of less than 3 hours on March 11, 1993. This left behind a more stable surface which does not tend to produce dusts. Subsequent storms, however, began eroding this crust, developing a thin sand layer that was rapidly mobilized in strong winds, and able to generate PM_{10} dusts by the saltation-abrasion mode. Once this occurred, the threshold wind velocity for dust events dropped sharply, and dust storms became large and more common.

These results support the findings of Gillette (WESTEC appendix, 1984) which indicated that the crusted Owens Lake Bed was not a major source of fine dust until wind velocities exceeded 25 m/s. This was very different from other types of surfaces tested, and set Owens (and Mono) Lake apart from non-playa sediments and soils. The effect was ascribed to the crusting of the surface, resulting in a surface depleted in particles capable of being resuspended. We have confirmed and extended these results, and observed three kinds of crusting:

1. Efflorescent, fragile white material that grows from complete wetting of the surface in late winter. On the South Sand Sheet this crust was destroyed in about 2 to 3 hours on March 11, 1993. Its impact on PM_{10} was not documented, but many fragments appeared to be too large to directly loft into PM_{10} dusts. After the rains of March 25, 1993, a cemented crust formed that began to form a new efflorescent crust by early April, only to be destroyed by sand abrasion in April and May.

2. A relatively hard, salt-silt-clay crust that underlies the fragile efflorescence above it. This crust slowly eroded from March 11 to March 24 at our sites, on a storm by storm basis. In areas in which the crust was intact, little PM_{10} dust was generated. As the crust was eroded, large "gray-beige" areas of broken crust with loose sand appeared. These areas were easily suspended by winds, and formed the major PM_{10} sources during the intense March storms, with a saltation-erosion mechanism generating particles as fine as 0.3 μm diameter.

3. A cemented crust that forms after rain storms in spring, summer, or fall, and by release of the water of hydration from salts in summer. This is a very sturdy crust that forms on dry sand/salt mixtures, cemented by salt and clay, that will even support vehicles (in extreme cases) and is highly resistant to dust formation. Until this crust was, in turn, eroded by saltation abrasion, dust production was sharply curtailed even in high winds. We were able to document the gradual erosion of this crust on the South Sand Sheet through the movement of loose sands, starting near the Dirty Socks Spring dunes and spreading northward, during summer 1993.

c. Generation of PM_{10} Dusts via Saltation

The most important results of this study were the confirmation of and the determination of causes of the "fetch effect" (field length effect), and the connection between sand abrasion and PM_{10} dusts. In the fetch effect, PM_{10} dust production rates rise as one moves downwind along a wind fetch. Some have hypothesized that it is caused by saltationinduced changes in a near surface boundary layer, an "avalanche effect," and/or changes in the land surface. In fact, we documented all three mechanisms at various times during March 1993 on the Owens Lake Bed. The dominating fetch effect mechanism at the large scale (>100 m), for all but a period of two hours on March 11, was the variation of threshold velocity on the playa surface. These results are consistent with the crust destruction mechanisms seen qualitatively in the visual and photographic studies. In the saltation/abrasion effect, motion of coarse particles over a salt plus silt crust breaks off fine particles that loft as dust. Direct measurements were made showing both a relative uniformity across the instrumented test array on the playa during each storm, plus sharply increasing dust concentrations in subsequent storms. The dust production rate climbed by a factor of over 100 during the March tests as the crust was destroyed. The connection between meteorology, sand motion, and dust production is shown in Figure 54.

Nature of dusts, optical properties, and transport

a. Nature and Optical Properties of PM_{10} Dusts

The detailed analysis of the dust storms, both by size-time-composition analyses and by photographic evidence, allow a direct Mie Theory calculation of optical properties of the dusts. What is shown is that the fine dusts that are optically efficient, D_{0e} are less than 2.5 µm, and are not only salts but also include an unprecedented concentration of fine soils that are absent in almost all other dust storms intensively studied (Gobi Desert, Sahara, many southwest US studies). The mass loading at local area residences (PM_{10} observed at 27,000 $\mu g/m^3$) is higher than at other locations in the USA, and because of the fine particle size, dusts will penetrate deeply into the lung. We also detailed the size and concentration of arsenic, and noted that dusts from some parts of the lake bed had greater concentrations than others.

b. PM_{10} Dust Transport Phenomena

Estimates of the dry deposition velocity and dust plume dilution show that under dust storm conditions the plume from Owens (Dry) Lake can be transported extreme distances. Average particle half distance was measured to range from 35 to 70 km, depending on wind speed. Furthermore, the steep slopes of the Sierra Nevada and White-Inyo Range tends to keep horizontal plume dilution low during dust transport up and down the Owens Valley, keeping mass concentrations high. Substantial plume dilution generally does not occur until it reaches Indian Wells Valley or Panamint Valley. However, the large fraction of fine particles generated at Owens (Dry) Lake will degrade visibility long after mass concentrations have reduced.

Anabatic ("upslope" or "valley") winds were frequently observed transporting dust into the Sierra Nevada and White-Inyo ranges. While we do not have sufficient historical data to

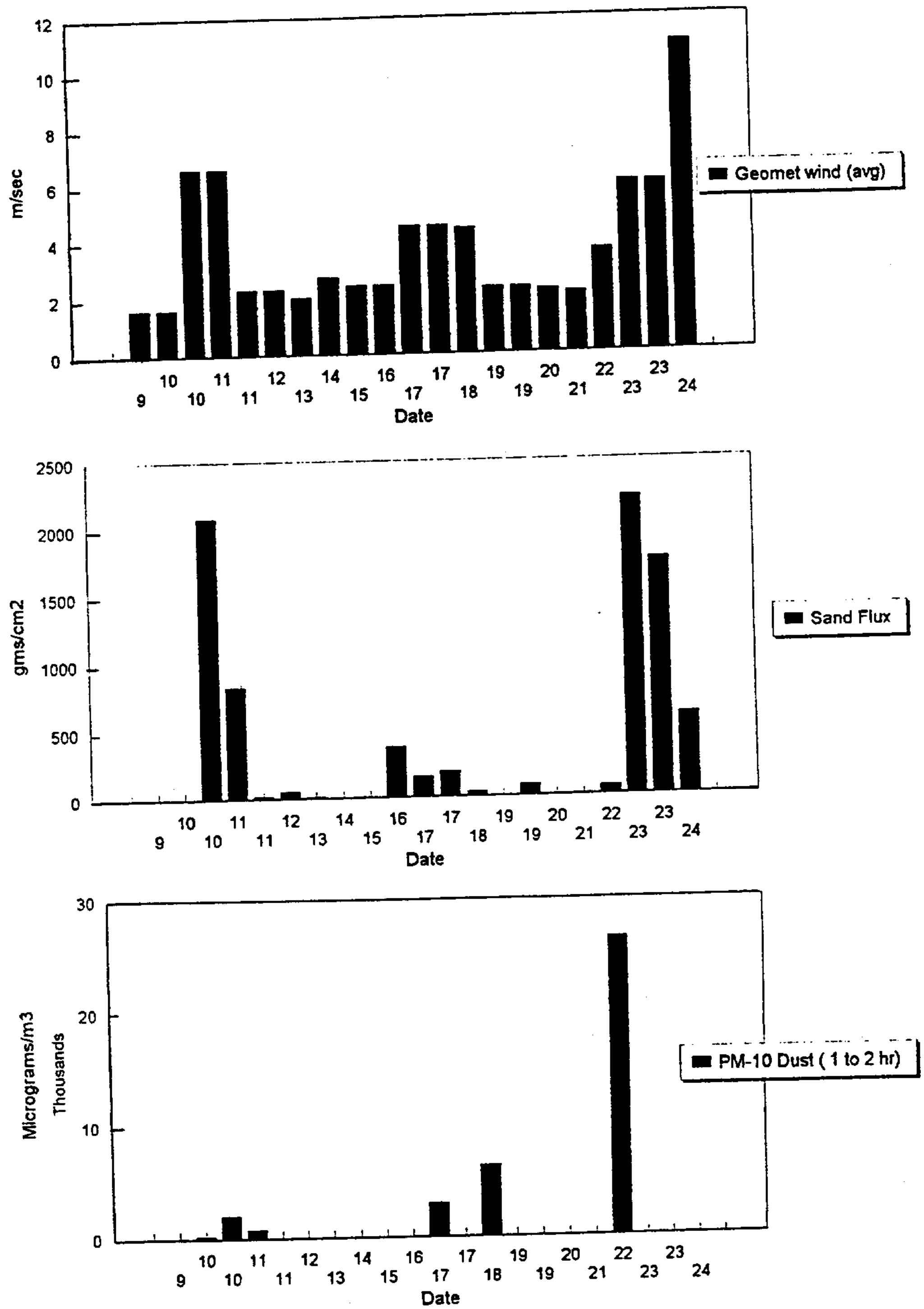


Figure 54. Meteorology, sand motion, and dust production in the March 1993 intensive, Lake Owens Dust Experiment.

estimate plume impact frequency into the region's numerous Class I and II airsheds, we did observe substantial amounts (concentration >400 $\mu g/m^3$) of dust transported into the John Muir Wilderness, Golden Trout Wilderness, and Ancient Bristlecone Pine Forest Area of Critical Ecological Concern, and we suspect minor intrusions into Sequoia and Kings Canyon National Parks. Anabatic winds are an expected meteorological phenomenon in the region and probably exist during most late morning and afternoon dust events. Conversely, catabatic ("downslope" or "mountain") winds combined with the stable planetary boundary layer probably prevent intrusion into these protected regions during most nighttime dust events. See Appendix F for an earlier observation of dust transport effects in the Inyo Mountains.

We have demonstrated a substantial impact on the Inyo National Forest and Panamint Valley, causing substantial degradation of ambient air quality and visibility. Pending the passage of the California Desert Act and the subsequent moving of the new Death Valley National Park boundary, the transport of Owens (Dry) Lake dust into the Panamint Valley could result in a violation of the Clean Air Act.

c. Impact at the Receptor Locations

Overall, ten years of 24 hour, one-day-in-six monitoring in the many communities in the region is not sufficient to assess exposure to dust and risk to the general public. Dust events can occur for short durations (less than a few hours) with extreme mass loadings. This is not reflected in 24 hour samples. While a sample may list the daily average PM_{10} below 400 $\mu g/m^3$, the mass loading for a portion of a storm may exceed 20,000 $\mu g/m^3$. Furthermore, the sampling does not take into account chemistry changes in the dust. Dust chemistry changed dramatically as a function of production location and playa conditions. Despite the close proximity of the samplers to the lake bed, plumes are frequently missed. For example, during several storms a portion of the town of Olancha was severely impacted while the GBUAPCD Olancha sampler was in relatively clean air.

Residents of the towns of Keeler and Olancha are regularly exposed to extremely high levels of PM_{10} dust (>10,000 $\mu g/m^3$, instantaneously) with at least 50% mass fraction below 5 μm. Variations in chemistry and exposure prohibit a direct assessment of possible health effects. Regardless, under the conditions present during most events, the nuisance effects are severe.

Although there was minimal intrusion of Owens dust into the Baker and G-1 ranges at the Naval Air Weapons Station, China Lake (NAWS, CL) during the spring 1993 intensive, in the fall 1991 study major intrusions were observed for two of the four events monitored with estimated mass loadings in excess of 1,000 $\mu g/m^3$. The geography of the region allowed for the efficient transport of dust into the range. Communications with NAWS, CL personnel have stated that the ranges are shut down from 2 to 8 times per year due to poor visibility, causing financial loss in the millions of dollars. Impacts at NAWS, CL are also generally felt at the cities of Ridgecrest and Inyokern (combined population approximately 50,000). Because of the fine aerodynamic size of the dust and the almost total removal of particles larger than 6 μm D_{ae}, measured PM_{10} levels from Owens (Dry) Lake dust events will have a relatively higher alveolar deposition than standard PM_{10} dust events.

d. Ecology

The establishment of vegetation on the Owens Lake playa has been recommended in previous studies as a natural method of dust suppression. We initiated a study of the natural and introduced vegetation patterns around Owens (Dry) Lake, especially those plant communities living on the lake bed in conditions of high alkalinity and/or salinity. These studies generated detailed information on the nature of the soil and water conditions necessary to support vegetation. The conclusions are, unsurprisingly, that native species such as saltbush, greasewood, and saltgrass have the highest probability of establishment in re-vegetated dunes. These species also encourage the most complex ecological communities, both fauna and flora. This conclusion supports the results of the revegetation test plots of the State Lands Commission WESTEC study (1984). The tamarisk, while potentially interesting as a species, has numerous negative impacts including a very high evapotranspiration rate even when drought stressed. This results in a local lowering of the water table and stress on other, often native, co-located species. It is not recommended for the Owens Lake playa.

Some may feel that any attempt to mitigate dust storms in Owens (Dry) Lake via vegetation lies in the realm of science fiction. Perhaps there is some truth to this (Appendix G).

RECOMMENDATIONS

This study has shown that the control of loose, coarse particles, prevention of the initiation of the saltation process, and protection of the crusts (efflorescent, salt, and cemented) will greatly diminish the generation of PM_{10} dusts from the Owens Lake playa.

The research carried out in the present study, together with prior work, has established that the Owens (Dry) Lake dust storms are potentially a major hazard to health and welfare. Three state standards are regularly violated – 24 hr PM_{10}, sulfates, visibility. At least one federal standard – 24 hr PM_{10} – is also violated, but what is more important, the magnitude of the violations is adequate to establish that in many years Owens (Dry) Lake dust storms deliver the worst 24 hr dust in the nation. The highest PM_{10} levels reported elsewhere in the USA are in the Columbia Plateau of Washington (Stewart, 1992), including a 24-hour reading of 1,689 $\mu g/m^3$ at Tri-Cities and a 12-hour reading of 10,875 $\mu g/m^3$ at T-16 Ranch on September 11, 1993 (Stetler, 1994). In the Owens Lake region on February 3, 1989, the GBUAPCD recorded a 24-hour PM_{10} concentration at Keeler of 1,861 $\mu g/m^3$ (GBUAPCD, 1994), and on December 14, 1993, the GBUAPCD TEOM sampler at Keeler recorded a maximum one-hour PM_{10} concentration of 4,477 $\mu g/m^3$ (Fitchette, 1993). On March 23, 1993, we recorded a 2-hour PM_{10} concentration of over 40,000 $\mu g/m^3$ on the Owens Lake playa, and on March 24, 1993 we recorded an instantaneous PM_{10} measurement on the Owens (Dry) Lake shoreline in excess of 27,000 $\mu g/m^3$.

Further, the nature of the dusts adds a major measure of uncertainty in their effects on health, since the particle sizes are far smaller than standard PM_{10} dusts and the composition is both unusual and disturbing. The dusts contain at least one known carcinogen, arsenic, in amounts that may also be the highest 24 hour values in California. Finally, this fine dust is rather efficiently carried great distances, impacting both human resources, welfare (including NAWS, CL range visibility and actual and potential Class I areas), and the environment, including the ancient bristlecone pines.

Thus the first recommendation is obvious:

1. Begin serious efforts at dust mitigation immediately.

It is our opinion that enough information is available to effectively and efficiently begin some mitigation today, with the benefit being improved efficiency and better techniques in future years from what we learn now. Further, we recommend that the information delivered (below) can be used to continually fine tune the mitigation efforts, directing the mitigation efforts towards those areas that are most involved in dust production and most resistant to controls. In Appendix I, we present our specific recommendations and strategies to implement dust mitigation at Owens (Dry) Lake.

In order to aid in accomplishing this task with maximum cost-efficiency, the informational resources in the area must be augmented.

2. We recommend continued use of the continuous PM_{10} monitor (a TEOM unit) at Keeler. It will greatly increase data collection, allowing development of sound statistical models in a shorter period of time. We further recommend co-locating it with the standard PM_{10} sampler.

3. We recommend that the USGS Desert Winds Project's Geomet tower on the South Sand Sheet continue in operation. This study has shown the vital role that the Geomet plays, providing a true picture of actual meteorological and geomorphic conditions in a local area of active dust plume formation on the playa.

4. We recommend that the GBUAPCD "A tower" on the North Sand Sheet be maintained in operation and upgraded to match the Geomet tower on the South Sand Sheet. The data should be made available promptly to all interested research scientists.

5. We recommend development and deployment of surface condition monitors to measure the presence of moisture in the surface, and discrete (weekly) measure of crust strength and other parameters at both sites.

6. We recommend continued operation of sand motion monitoring devices at the South and Northeast Sand Sheets, with an effort to better calibrate the readings in terms of quantitative sand motion.

7. We recommend the use of continuous recording aerosol monitors at both sites. We realize that the infrastructure will not allow TEOMs on the lake bed, but other devices should be evaluated, including sequential filter samplers, SMART drum samplers, etc.

8. We recommend installation and operation of two (or more) cameras at elevated sites overlooking the lake bed, with at least one photograph/30 minutes during daylight hours. One would be at Cerro Gordo, to view the Northeast Sand Sheet; the other in the Sierra Nevada above Olancha for the South Sand Sheet. A third might be on the Horseshoe Meadows Road.

9. We recommend that these data be continuously evaluated, independently, by local and state agencies to provide both a detailed measure of the violations and a measure of the improvement subsequent to mitigation efforts.

10. We recommend increased dust monitoring in ecologically sensitive areas, such as the Ancient Bristlecone Pine Forest, to better quantify the impacts of Owens (Dry) Lake dusts on plants. We recall that Lake Tahoe vegetation is very salt-sensitive, and that Owens (Dry) Lake dusts are salty.

11. We recommend that the costs of the increased surveillance be borne by the Los Angeles Department of Water and Power, in parallel with immediate mitigation efforts. While such support is explicitly mandated by California law, we also feel that there would be major benefits to LADWP in long term cost containment in the mitigation effort.

12. Finally, we recommend that a new Owens Lake Task Force be constituted, under state mandate, with freedom to exercise the regulatory authority that the agencies possess. The task at Owens (Dry) Lake is daunting, and the local resources limited. Available state and federal resources, intellectual as well as operational, should be exercised to help GBUAPCD and LADWP achieve rapid progress in dust reduction at Owens (Dry) Lake.

REFERENCES AND BIBLIOGRAPHY

Aerovironment Corp., 1992, Owens Lake Phase II Dust Mitigation Studies, Vol. 1. Report prepared for Los Angeles Department of Water and Power.

Allen, T., 1975. Particle Size Measurement, 2nd Edition. Chapman and Hall, London:

Amdur, M.O, J. Bayles, V. Urgo and D.W. Underhill, 1987. Comparative irritatant potency of sulfate salts. Environmental Research 16: 1-8.

Anderson, R. and P. Haff, 1991. Wind modification and bed response during saltation of sand in air. Acta Mechanica, suppl. 1: 21-51.

Baron, P.A., 1986. Calibration and Use of the Aerodynamic Particle Sizer (APS 3300). Aerosol Science and Technology 5: 55-67.

Barone, J.B., B.H. Kusko, L.A. Ashbaugh and T.A. Cahill, 1979. A Study of Ambient Aerosols in the Owens Valley Area. Final Report to the California Air Resources Board on Contract No. A7-178-30.

Barone, J.B., L.L. Ashbaugh, B.H. Kusko, and T.A. Cahill, 1981. The Effect of Owens Dry Lake on Air Quality in the Owens Valley with Implications of the Mono Lake Area. In: Radke, P., ed., Atmospheric Aerosols: Source/ Air Quality Relationships. American Chemical Society Symposium Series 167: 327-346.

Belanger, L., J.F. Giroux and J. Bedford, 1990. Effects of Goose Grazing on the quality of *Scirpus Americanus* rhizomes. Canadian Journal of Zoology 68: 1012-1014.

Bradley, E.F., 1968. A micrometeorological study of velocity profiles and surface drag in the region modified by surface roughness. Quarterly Journal of the Royal Meteorological Society 94: 361-379.

Buckley, R., 1987. The effect of sparse vegetation on the transport of dune sand by wind. Nature 325: 426-428.

Cahill, T.A., R.A. Eldred, D.J. Shadoan, P.J. Feeney, B.H. Kusko, and Y. Matsuda, 1984. Complete elemental analysis of aerosols: PIXE, FAST, LIPM, and Mass, Nuclear Instruments and Methods in Physics Research, B3: 291-295.

Cahill, T.A., B.H. Kusko, and T.E. Gill, 1986. Dust storms at Mono and Owens Lakes, California. Proceedings of the 17th Binghamton Geomorphology Symposium on Aeolian Geomorphology. University of Guelph, Canada, p. 37.

Cahill, T.A. and T.E. Gill, 1987. Air Quality at Mono Lake. University of California Water Resources Center Report 68, Appendix D.

Cahill, T.A, P.J. Feeney, and R.A. Eldred, 1987. Size-time composition profile of aerosols using the DRUM sampler. Nuclear Instruments and Methods in Physics Research B22: 344-348.

Cahill, T.A., H. Annegam, D. Ewell, B. Pedersen, K. Bowers, D. Campbell, P. Beveridge and R. A. Eldred, 1989. Monitoring of Atmospheric Particles and Ozone in Sequoia National Park: 1985-1987. Final report prepared for the California Air Resources Board on Contract No. A5-180-32.

Cahill, T.A., R.A. Eldred, P. Feeney, P.J. Beveridge, and L.K. Wilkinson, 1990. The stacked filter unit revisited. Transactions of the Air and Waste Management Association 17: 213-222.

Cahill, T.A., T.E. Gill, and E.A. Gearhart, 1993. Study of Sand Motion on the South Sand Sheet, Owens Lake, Report to the California State Lands Commission, June 14, 1993, on Contract No. C-9175.

Cahill, T.A., T.E. Gill, J.S. Reid, E.A. Gearhart and D.A. Gillette, 1994. Sand motion and PM_{10} aerosols from Owens (Dry) Lake. In: Lancaster, N. ed., Abstracts of the Workshop: Response of Eolian Processes to Global Change. Desert Research Institute Quaternary Sciences Center Occasional Paper 2:15: complete manuscript submitted to Earth Surface Processes and Landforms.

California Air Resources Board, 1979- 1993. "Blue Sky Reports."

California Department of Fish and Game, 1987. Ecosystem Classification Handbook. Report FSH 12/87 R-1 SUPP 1, page 4.51--3.

Chavez, P.S. Jr., and D.J. MacKinnon, 1994. Automatic Detection of Vegetation Changes in the Southwest United States using Remotely Sensed Images. Photogrammetric Engineering and Remote Sensing 60:571-583.

Chepil, W. S., 1946. Dynamics of wind erosion, V, Cumulative intensity of soil drifting across eroding fields. Soil Science 61: 257-263.

Chepil, W. S., 1957. Width of field strips to control wind erosion. Kansas State Agricultural Experiment Station Technical Bulletin 92.

Chepil, W. S., and R. A. Milne, 1939. Comparative study of soil drifting in the field and in a wind tunnel. Scientific Agriculture No. 249.

Cochran, G.F., T.M. Mihevic, S.W. Tyler, and T.J. Lopes, 1988. Study of salt crust formation mechanisms on Owens (Dry) Lake, California. Desert Research Institute Publication Series No. 41108.

Cox, W., 1991. Personal Communication.

Dahlgren, R.A., 1993. Salt and Nutrient Dynamics in Vegetation, Soil and Groundwater of the Owens Playa System. Report of the Biogeochemistry Laboratory, Department of Land Air and Water Resources, University of California, Davis.

d'Almeida, G.A., and L. Shutz, 1983. Number, mass, and volume distributions of mineral aerosols and soils of the Sahara. Climate and Applied Meteorology 22: 233-243.

DeDecker, M., 1991. Personal communication.

Eldred, R. and Cahill, T., 1991. Particulate Measurements in the IMPROVE Network: A Guide to Interpret Seasonal Summaries. Report to the National Park Service by Crocker Nuclear Laboratory, University of California, Davis, 16pp.

Fitchette, T., 1993. Owens Lake dust storms blow away air standards. Inyo Register, Bishop, CA, December 19, 1993, p.A-1.

Fryrear, D.W., 1986. A field dust sampler. Journal of Soil and Water Conservation 41: 117-120.

Fryrear, D.W., 1994. Personal communication.

Gaines, D., and M DeDecker, 1992. Owens Valley and Mono Lake: I. Dying of Thirst. Fremontia 10(3): 3-10.

GBUAPCD, 1993a. Written submission to the California Water Resources Control Board, re: Mono Lake Water Rights Draft Environmental Impact Report.

GBUAPCD, 1993b. PM_{10} Data for Keeler, California, March 1993.

GBUAPCD, 1994. Owens Valley PM_{10} Planning Area Best Available Control Measures State Implementation Plan.

Gill, T.E., 1994. Eolian sediments generated by anthropogenic disturbance of playas: Human impact on the geomorphic system, geomorphic impact on the human system. In: Lancaster, N. ed., Abstracts of the Workshop: Response of Eolian Processes to Global Change. Desert Research Institute Quaternary Sciences Center Occasional Paper 2: 39: complete manuscript submitted to Geomorphology.

Gill, T.E. and T.A. Cahill, 1992. Drying saline lake beds: A regionally-significant PM_{10} source. Transactions of the Air and Waste Management Association 22: 440-454.

Gill, T.E. and D.A. Gillette, 1991. Owens Lake: A natural laboratory for aridification, playa desiccation and desert dust. Geological Society of America Abstracts with Programs 23(5): 462.

Gillette, D.A. and T.R. Walker, 1977. Characteristics of airborne particles produced by wind erosion of sandy soil, high plains of West Texas. Soil Science 123: 97-110.

Gillette, D.A., J. Adams, A. Endo, D. Smith and R. Kihl, 1980. Threshold Velocities for the Input of Soil Particles into the Air by Desert Soils. Journal of Geophysical Research 85: 5621-5630.

Gillette, D.A., 1981. Production of dust that may be carried great distances. Geological Society of America Special Papers 186: 11-36.

Gillette, D. A., J. Adams, D. Muhs, and R. Kihl, 1982. Threshold friction velocities and rupture moduli for crusted desert soils for the input of soil particles into the air. Journal of Geophysical Research 87: 9003-9015.

Gillette, D.A., 1984. Threshold Friction Velocities and Moduli of Rupture at Owens Lake, California. Appendix to: WESTEC, Inc. Results of Test Plot Studies at Owens Dry Lake, Inyo County, California. Report to California State Lands Commission.

Gillette, D. A. and P. H. Stockton, 1989. The effect of nonerodible particles on wind erosion of erodible surfaces. Journal of Geophysical. Research 94: 12885-12893.

Gillette, D.A., G. Herbert, P.H. Stockton and F.R. Owen, 1994. Causes of the fetch effect in wind erosion. Manuscript submitted to Earth Surface Processes and Landforms.

Gomes, L., G. Bergametti, G. Coude-Gaussen, and P. Rognon, 1990. Sub micron desert dusts: A sandblasting process. Journal of Geophysical Research 95: 13927-13935.

Goudie, A.S., M. Anderson, T. Burt, J. Lewin, K. Richards, B. Whalley, and P. Worsley, 1981. Geomorphological Techniques. George Allen and Unwin, Boston.

Gregory, J. M. and J. Borrelli, 1986. The Texas Tech wind erosion equation. Papers of the American Society of Agricultural Engineers, No. 86-2528.

Hardebeck, E., 1992. Personal Communication.

Hensen, D.J., P. Dayanandon, P.B. Kaufman and J.D. Brotherson, 1976. Ecological adaptation of salt marsh grass, *Distichlis spicata* (Graminacae), and environmental factors affecting its growth and distribution. American Journal of Botany 63: 635-650.

Herbert, F., 1965. Dune. Ace Books, New York.

Kusko, B.H., J.B. Barone, and T.A. Cahill, 1981. The effect of Mono Lake on the air quality in the Mono Lake region. Final Report to the California Air Resources Board on Contract A1-144-32.

Kusko, B.H. and T.A. Cahill, 1984. Study of particle episodes at Mono Lake. Final Report to the California Air Resources Board on Contract A9-147-31.

MacKinnon, D.J. and P.S. Chavez Jr., 1993. Dust Storms. Earth 2(3): 60-65.

MacKinnon, D.J., P.S. Chavez, R.S. Fraser, T.C. Johnson and D.A. Gillette, 1994. Analysis of GOES/VISSR Satellite Image Data Acquired During the March 11, 1993 Dust Storm at Owens Lake California. In: Lancaster, N. ed., Abstracts of the Workshop: Response of Eolian Processes to Global Change. Desert Research Institute Quaternary Sciences Center Occasional Paper 2: 77-78. Full manuscript submitted to Geomorphology.

Marchand, D.E., 1970. Soil contamination in the White Mountains, eastern California. Geological Society of America Bulletin 81: 2497-2505.

Marshall, I.A., J.P. Mitchell, and W.D. Griffiths, 1991. The behavior of Regular Shaped Non-Spherical Particles in a TSI Aerodynamic Particle Sizer. Journal of Aerosol Science 22: 73-89.

McCauley, J., Breed, C., Helm, P., Billingsley, G., McKinnon, D., Grolier, M., and McCauley, C., 1984. The Desert Winds Project. U.S. Geological Survey Bulletin 1634.

McClung, W., 1994. Personal Communication.

McKell, C.M., 1986. Propagation and establishment of plants on arid saline land. Reclamation and Revegatation Research 5: 363-375.

Meyer, R.E. (ed.), 1972. Waves on Beaches and Resulting Sediment Transport. Academic Press, New York.

Miller, I and J. Freund, 1977. Probability and Statistics for Engineers, 2nd Edition Prentice-Hall, Englewood Cliffs, New Jersey.

Nadeau, R.A., 1950. The Water Seekers. Peregrine Smith, Santa Barbara, CA.

Ono, D., 1991. Report presented to the Owens Lake Advisory Group. Fall Meeting, Independence, CA.

Ono, D.M., M.F. Knop and J. Parker, 1994. Instruments and Techniques for Measuring Windblown Dust and PM_{10} at Owens Lake, California. Annual Meeting of the Air and Waste Management Association, Cincinnati, OH, June 1994. Paper No. 94-FA145.05, 16 pp.

Ono, D., 1994. Personal communication.

Owen, P.R., 1964. Saltation of uniform sand grains in air. Journal of Fluid Mechanics 20: 225-242.

Owens Lake Task Group, University of California, Davis (R.G. Flocchini, chair, and 19 others), 1991. Proposal to the State Lands Commission for the accelerated mitigation of the Owens Lake Bed in conjunction with the Great Basin Unified Air Pollution Control District (GBUAPCD), August 1991.

Panofsky, H, and J. Dutton, 1984. Atmospheric Turbulence Models and Methods for Engineering Applications. Wiley Interscience, New York, p. 129.

Patterson, E.M. and D.A. Gillette, 1977. Commonalties in measured size distributions for aerosols having a soil derived component. Journal of Geophysical Research 82: 2074-2082.

Patterson, Michael, 1993. Personal communication.

Pomeroy, J.W., D.M. Gray and P.G. Landine, 1993. The prairie blowing snow model: characteristics, validation, operation. Journal of Hydrology 144: 165-192.

Portor, J.R., and D.W. Lawlor, 1991. Plant Growth: interaction with nutrient and environment. Cambridge University Press, New York.

Prodgers, R.A. and W.P. Inskeep, 1991. Heavy metal tolerance of inland saltgrass (*Distichlis spicata*). Great Basin Naturalist 51: 271-278.

Raabe, O.G., D.A. Braaten, R.L. Axelbaum, S.V. Teague, and T.A. Cahill, 1988. Calibration studies of the DRUM impactor. Journal of Aerosol Science 19: 183-195.

Rasmussen, K.R. and J. Iversen, 1994. Personal Communication.

Raupach, M., 1991. Saltation layers, vegetation canopies and roughness lengths, Acta Mechanica, (Suppl) 1: 83-96.

Reid, J.S., T.A. Cahill, R.G. Flocchini, B.R. White, M.R. Dunlap, and D.M. Ono, 1993. Characteristics of Fugitive Dusts Generated at Owens Lake (dry), California, During the Fall Dust Season. Annual Meeting of the Air and Waste Management Association, Boulder, CO, June 1993, paper No. A1200, 12 pp.

Reinking, R.F., L.A. Mathews, and C. Saint Amand, 1979. Dust storms due to desiccation of Owens Lake. Proceedings of the International Conference on Environmental Sensing and Assessment, Vol. 2, Paper 37-4.

Saint Amand, P., L. Mathews, C. Gaines, and R. Reinking, 1986. Dust storms from Owens and Mono Lakes. Naval Weapons Center Technical Publications, No. 6731.

Saint Amand, P., C. Gaines, and C. Saint Amand, 1987. Owens Lake: an ionic soap opera staged on a natric playa. Geological Society of America Centennial Field Guide-Cordilleran Section, Geological Society of America, Boulder, CO, 145-150.

Seinfeld, J.H., 1986. Atmospheric Chemistry and Physics of Air Pollution. John Wiley and Sons, New York, pp. 639-650.

Seliskar, D.M., 1990. The role of waterlogging and sand accretion in modulating the morphology of the dry slack plant *Scirpus Americanus*. Canadian Journal of Botany 68: 1780-1787.

Shao, Y. and M. R. Raupach, 1992. The overshoot and equilibrium of saltation. Journal of.Geophysical. Research 97: 20559-20564.

Shao, Y., G.H. McTainsh, J.F. Leys, and M.R. Raupach, 1993. Efficiencies of sediment samplers for wind erosion measurements. Australian Journal of Soil Research 31: 519-532.

Spear, B.R., 1977. Owens Valley Today. In: Southern Inyo American Association of Retired Persons (ed.,) Saga of Inyo County. Taylor Publishing, Covina, CA, pp. 54-55.

Stetler, L., 1994. Wind Erosion, PM_{10} Emissions, and Dry-Land Farming on the Columbia Plateau. In: Lancaster, N., ed., Abstracts of the Workshop: Response of Eolian Processes to Global Change. Desert Research Institute Quaternary Sciences Center Occasional Paper 2: 103-106.

Stewart, B., 1992. SIP Development for an Urban Nonattainment Area Impacted by Rural Fugitive Dust. Transactions of the Air and Waste Management Association 22: 936-945.

Stockton, P. H., and D. A. Gillette, 1990. Field measurement of the sheltering effect of vegetation on erodible land surfaces. Land Degradation and Rehabilitation 2: 77-85.

Stout, J. E., 1990. Wind erosion within a simple field. Transactions of the American Society of Agricultural Engineers 33: 1597-1600.

Stout, J.E., 1993. Personal Communication.

Vorster, P., 1992. The Development and Decline of Agriculture in the Owens Valley. In: Hall, C.A., Jr., V. Doyle-Jones, and B. Widawski, eds. The History of Water: Eastern Sierra Nevada, Owens Valley, White-Inyo Mountains. University of California, Los Angeles, 268-284.

WESTEC Services Inc., 1984. Results of test plot studies at Owens dry Lake, Inyo County, California. Report to the California State Lands Commission.

White, B.R. and H.M. Cho, 1994. Wind-tunnel simulation of Owens (Dry) Lake sand fences. In: Lancaster, N., ed., Abstracts of the Workshop: Response of Eolian Processes to Global Change. Desert Research Institute Quaternary Sciences Center Occasional Paper 2: 117-119

Wilshire, H.G., 1980. Human Causes of Accelerated Wind Erosion in California's Deserts. In: Coates, D.R. and J.D. Vitek, eds. Thresholds in Geomorphology. George Allen and Unwin, Boston, pp. 415-433.

Yau, M.L., 1993. Vegetation and Soil Analysis at Spring and Well Sites at Owens (Dry) Lake, California. Thesis (M.S., Ecology), University of California, Davis.

Zar, J.H., 1985. Biostatistical analysis. Prentice-Hall, New York.

List of publications and professional presentations related to this contract

1. Gill, Thomas E. and Dale A. Gillette (1991). Owens Lake: A natural laboratory for aridification, playa desiccation and desert dust. Presented at: the Geological Society of America Annual Meeting, San Diego, CA, October 1991. Abstract published in: Geological Society of America Abstracts and Programs 23(5): A426.

2. Gill, Thomas E. and Thomas A. Cahill (1992). Playa-generated dust storms from Owens Lake. Presented at: the Fourth University of California White Mountain Research Station Symposium, Bishop, CA, September 1991. Published in: Hall, Clarence A. Jr., Victoria Doyle-Jones and Barbara Widawski (Editors) (1992). The History of Water: Eastern Sierra Nevada, Owens Valley, White-Inyo Mountains. University of California, Los Angeles, pp. 63- 73.

3. Gill, Thomas E. and Thomas A. Cahill (1992). Drying saline lake beds: A regionally significant PM_{10} source. Presented at: the Air & Waste Management Association/U.S. EPA Specialty Conference on PM_{10} Standards and Nontraditional Particulate Source Controls, Scottsdale, AZ, January 1992. Published in: Transactions of the Air and Waste Management Association 22: 440- 454.

4. Flocchini, Robert G., Thomas A. Cahill, Jeffrey S. Reid and Thomas E. Gill (1992). Measurement of aerosols from the Owens Dry Lake bed. Presented at: the Conference on Visibility and Fine Particles, Vienna, Austria, September 1992.

5. Reid, Jeff S., Thomas A. Cahill and Michael R. Dunlap (1992). TEM and SEM based techniques for determining particle characteristics of Owens Lake dusts. Presented at: the Annual Meeting of the American Association for Aerosol Research, San Francisco, CA, October 1992.

6. Reid, Jeffrey S., Thomas A. Cahill, Robert G. Flocchini, Bruce White, Michael R. Dunlap and Duane M. Ono (1993). Characteristics of fugitive dusts generated at Owens Lake (dry), California, during the fall dust season. Presented at: the Annual Meeting of the Air and Waste Management Association, Denver, CO, June 1993. Published in: Proceedings of the Annual Meeting of the Air and Waste Management Association, vol. 86, Paper No. A1200, 12pp.

7. Gill, Thomas E. (1994). Eolian sediments generated by anthropogenic disturbance of playas: Human impact on the geomorphic system, geomorphic impact on the human system. Presented at: the Conference on Eolian Response to Global Change, Zzyzx, CA, March 1994. Abstract published in: Desert Research Institute Quaternary Sciences Center, Occasional Paper No. 2, p. 39. Manuscript submitted to Geomorphology.

8. Cahill, Thomas A., Thomas E. Gill, Jeffrey S. Reid, Elizabeth A. Gearhart and Dale A. Gillette (1994). Saltating particles, playa crusts and dust aerosols from Owens (Dry) Lake, California. Presented at: the Conference on Eolian Response to Global Change, Zzyzx, CA, March 1994. Abstract published in: Desert Research Institute Quaternary Sciences Center, Occasional Paper No. 2, p. 15. Manuscript submitted to Earth Surface Processes and Landforms.

9. Gillette, Dale, Gary Herbert, Paul H. Stockton, and P.R. Owen (1994). Causes of the fetch effect in wind erosion. Presented at: the Conference on Eolian Response to Global Change, Zzyzx, CA, March 1994. Abstract published in: Desert Research Institute Quaternary Sciences Center, Occasional Paper No. 2, p. 41. Manuscript submitted to Earth Surface Processes and Landforms.

10. Reid, Jeffrey S., Robert G. Flocchini, Thomas A. Cahill, Robert S. Ruth and Daniel P. Salgado (1994). Local meteorological, transport and source aerosol characteristics of late autumn Owens Lake (dry) dust storms. Published in Atmospheric Environment 28: 1699- 1706.

GLOSSARY OF ACRONYMS

APCO	Air Pollution Control Officer
APS	Aerodynamic Particle Sizer
ARB	Air Resources Board (California)
ARL	NOAA Air Resources Laboratory
AVHRR	Advanced Very High Resolution Radiometer
BACM SIP	Best Available Control Methods State Implementation Plan
BSNE	Big Springs Number Eight (passive dust sampler)
CIRES	Cooperative Institute for Research in Environmental Sciences, Colorado State University
CORI	Community and Organization Research Institute, University of California, Santa Barbara
D_{ae}	Effective aerodynamic diameter
D_{oe}	Effective optical diameter
DRUM	Davis Rotating Unit for Monitoring (aerosol sampler)
EDAX	Energy Dispersive Analysis of X-rays
GBUAPCD	Great Basin Unified Air Pollution Control District, Bishop, CA.
GEOMET	Geological - Meteorological (monitoring and data collection system, U.S. Geological Survey)
GOES	Geostationary Operational Environmental Satellite
IMPROVE	Interagency Monitoring of Protected Visual Environments (research program)
LAC	Laser Aerosol Counter
LADWP	Los Angeles Department of Water and Power
LIDAR	Light Detection and Ranging
LODE	Lake Owens Dust Experiment (an interagency international field study, March 1993)
MODDM	Mono-Owens Davis Dust Model
MSL	(elevation with reference to) Mean Sea Level
NAWS, CL	Naval Air Weapons Station, China Lake (California)
NIOSH	National Institute for Occupational Safety and Health
NOAA	National Oceanic and Atmospheric Administration
PBL	Planetary Boundary Layer
PFS	Portable Filter Sampler (aerosol sampler)
PIXE	Proton-Induced X-ray Emission (method of spectrometry)
PM_{10}	Particulate Matter 10 Microns or less in aerodynamic diameter
PST	Pacific Standard Time
QA	Quality Analysis
SEM	Scanning Electron Microscopy
SFU	Stacked Filter Unit (aerosol sampler)
SLC	State Lands Commission (California)
SMART	Solar Monitoring of Aerosols in Remote Terrain (aerosol sampler)

TEOM	Tapered Element Oscillating Microbalance (aerosol sampler)
TSP	Total Suspended Particulates
UCD	University of California at Davis
USDA	United States Department of Agriculture
USGS	United States Geological Survey
WESTEC	WESTEC Services, Inc. (a consulting firm)

GLOSSARY OF TERMS

albedo = ratio of the amount of radiation reflected by a body to the amount incident upon it

alveoli = functional unit of the lung, including a membrane across which carbon dioxide and oxygen diffuse

anabatic wind = generally shallow, unstable upslope windflow during daytime due to surface heating

$\mathbf{b_{extinction}}$ = parameter that defines extinction of light in a beam

$\mathbf{b_{scatt}}$ = parameter that defines scattering of light from a beam

catabatic wind = downslope windflow, generally during nighttime

Class I airshed = pristine area protected against degradation by the 1977 Clean Air Act

clast = an individual grain of sediment or rock produced by the disintegration of a larger grain

deposition velocity = effective velocity describing the rate at which particles are removed from the atmosphere

effective aerodynamic diameter = diameter that gives the behavior of an equivalent sphere in air

effective optical diameter = diameter that gives the behavior of an equivalent sphere with regards to light

efflorescence = a powdery surface deposit of minerals produced by evaporation

evaporite = mineral deposit as a result of the evaporation of water

evapotranspiration = combined loss of water to the atmosphere by evaporation and transpiration (transfer of water vapor to atmosphere by plants)

fetch = continuous flat surface over which a sustained wind blows without obstruction

fetch effect = process that describes the observed increase of wind-eroded material as one moves downwind in a source area

field length effect = same as FETCH EFFECT

fulgurite = a rock formed from fused sediments caused by lightning striking the earth's surface, often rodlike or spike-shaped

friction velocity = effective velocity in the presence of a fixed surface

intervalometer = device to measure sequential intervals of length, depth, height, etc.

Mie theory = a theory used to describe characteristics of light scattering by particles, where the wavelength of light is comparable to particle size

nadir = the point where the direction of a plumb line extended below the horizon meets the celestial sphere. Its direct opposite is known as the zenith

nephelometer = device that measures b_{scatt} in a light beam

orographic = relating to the lifting of moist air above a mountain

path radiance = sunlight scattered to an observer from along sight path

pixel = individual picture element in a remote sensing image

playa = a desert basin that is at least seasonally dry: dry lake bed

reconstructed mass = a measurement of the total mass of an aerosol sample, excluding nitrates and residual water on the particles, gained by summing the masses of its individual chemical constituents obtained by analytical techniques (Eldred and Cahill, 1991)

roughness height = see ROUGHNESS LENGTH

roughness length = height above the surface at which wind velocity extrapolates to zero. This parameter controls the wind speed profile near the ground.

saltation = the process by which a particle is picked up in a stream of fluid, flung upward in a hopping motion, and then settles to the stream floor at a point downstream, as it is too heavy to remain in suspension

sand run = sand flux (g/cm^2) times wind run (km), representing both the mass of sand that crosses an area and the total distance the sand has traveled across the surface.

Soret effect = the effect by which dissolved salts in solution become most concentrated in that area of the solution where the temperature is lowest

sorting = measure of the uniformity of particle size in a sediment, based on the statistical spread of a particle-size-frequency distribution

Stokesian flow = airflow influenced by drag force

threshold friction velocity = Friction velocity above which steady wind erosion of the soil begins

valley wind = up-valley windflow, maximum velocity near the surface, towards surrounding highlands

zenith = see NADIR

APPENDIX A

RESULTS OF TEST PLOT STUDIES AT
OWENS DRY LAKE, INYO COUNTY, CALIFORNIA

Prepared For:

State Lands Commission
245 W. Broadway, Suite 425
Long Beach, California 90802

Prepared By:

WESTEC Services, Inc.
3211 Fifth Avenue
San Diego, California 92103

March 1984

EXECUTIVE SUMMARY

INTRODUCTION AND SCOPE

This report summarizes a 2-year study at Owens Dry lake, Owens Valley, California. This lake has been the source of heavy particulate emissions violating state and federal air standards which represent levels of air quality necessary, with an adequate safety margin, to protect the public health.

This study focused upon the establishment of an approximately 100-acre test plot on the lake bed surface to test the feasibility of various potential dust control measures on a micro-scale. Major objectives of the study included:

1. Determine the feasibility of using vegetation to control dust emissions on the lake bed surface.
2. Analyze the effectiveness of various types, sizes, and configurations of wooden sand fences in the trapping and control of blowing sands.
3. Analyze the feasibility of other nonvegetative methods to control particulate emissions. These methods included leaching pits, small sized barriers, and use of soil stabilizing chemicals.
4. Monitor meteorological conditions during the 2-year studies to determine wind patterns on a diurnal as well as seasonal basis. Monitoring was conducted at the study plot as well as on the eastern and western lakeshore.
5. Conduct limited air quality studies during high wind episodes.
6. Conduct a preliminary lake bed surface analysis on the eastern portion of the lake bed in order to identify significant particulate source areas.

It should be noted that funding restrictions limited the study to a 2-year program so that multiyear vegetation and meteorological data could not be obtained.

METHODS

The study was divided into vegetative, nonvegetative, meteorological, air quality and lake bed survey components. Four native species (*Atriplex parryi*, *Sarcobatus vermiculatus*, *Distichlis spicata*, and *Sporobolus airoides*) and one non-native species (*Tamarix aphylla*) were planted on dune sand and unaltered lake bed surface. Plants were maintained by a drip irrigation system throughout the summer of 1982 and given initial watering during the spring of 1983.

The major component of the nonvegetative experiments was the construction of a sand fence system. Six separate sand fences were constructed. Each was comprised of two fences set parallel to each other at varying separation distances. Separations selected were 50, 100, 200, 400, 800, and 1320 feet. Soil stabilization chemicals were tested on the lake bed surface. Two plastic polymers and magnesium chloride were sprayed on the lake bed and upon dune sand. A leaching plot system and a plot containing crossed railroad ties were also tested during the study.

Three weather stations erected on 30-foot towers were placed at the study plot and on the eastern and western lakeshore. Wind direction and speed were measured at all locations. Wind profiles were obtained at the study plot site.

Air quality studies consisted of two components. The first component consisted of wind tunnel experiments to determine threshold velocities of the lake bed crust and the dune sands. The second component consisted of very limited particulate monitoring utilizing a Lundgren impactor with four particulate cut-points pointed into the wind during sand/dust storms. A two-stage stacked filter unit was deployed atop the meteorological tower to measure the chemical composition and volume of dust near the surface and at 30 feet above ground.

A lake bed survey was conducted during the spring of 1983 to sample the lake bed surface composition. This study characterized the lake bed crust as to general dust emitting characteristics.

RESULTS AND DISCUSSIONS

With the exception of Tamarix aphylla, the other four plant species survived to the end of the experiment. Plant survival and growth was higher in the plots containing dune sand than upon the unaltered lake bed surface. The intensive care and water required to maintain the vegetation would make any large-scale dust stabilization program utilizing vegetation impractical.

The use of snow fences to form barriers to sand flow across Owens Lake has been relatively successful. Large amounts of sand have been collected by all of the experimental systems and the accumulation per linear foot exceeds projected values by 100-200 percent. The use of the dual fence system does not appear to provide major additional benefit in light of sand volumes collected at fence systems set 800 and 1320 feet apart.

Leaching experiments did result in some decline in salt concentrations of the lake bed. The leaching of lake bed deposits does not appear feasible, particularly on a large-scale, due to the large amounts of water required and the heavy clay concentration and silt deposits in the low lake bed area. It is possible that enhanced near-shoreline leaching might be feasible but would require large amounts of water.

Chemical stabilization appears not to be feasible on a lakewide basis since a crust of less strength than the natural crust was formed. Since these chemicals were not tested on the areas of Powder Aggregate, it may be appropriate to test these solutions on small plots in these future studies.

Meteorological studies indicated that frequent moderately strong winds occur on summer afternoons. Less frequent, but more intensive high wind eposides occurred during winter storms. Winds were in a north-south or south-north direction.

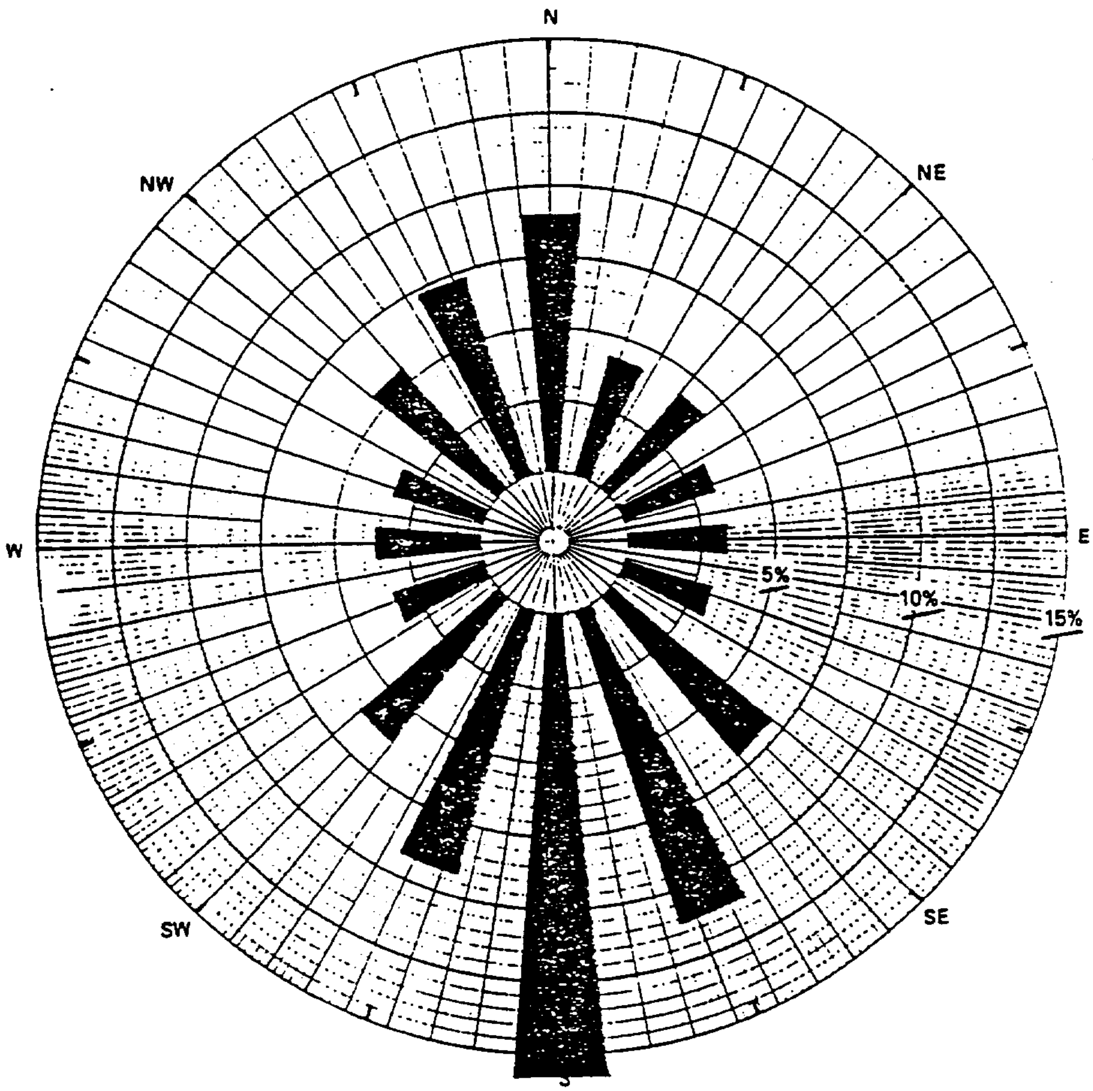
Wind tunnel experiments indicate that a majority of the crust on the lake bed surface was relatively stable. Abrasion by wind-driven sand was required to loft significant amounts of salt. Lake bed surveys indicated that a small area classified as Powder Aggregate required no sand blasting to loft significant quantities of dust.

CONCLUSIONS AND RECOMMENDATIONS

Two factors appear to be interacting in producing dust episodes at Owens Lake. One factor involves lofting of particulates from the areas of Powder Aggregate without sand abrasion. The second factor involves generation of a substantial amount of dust by sand abrasion of the relatively stable crust on the majority of the lake bed. The percentage contribution of each factor to the overall dust problem at Owens Lake cannot be determined at this time, although it is probable that both factors are significant.

A pilot program was recommended as the next stage in dust control activities at Owens Lake. It was proposed that 6 miles of sand fence in 1-mile segments should be placed in a position to trap blowing sand from established sand sources. At least two segments should be placed in the Powder Aggregate areas to assess the ability of the fences to reduce dust lofting from this volatile area. Dust control chemical experiments should also be conducted in this area. Additional studies on the chemical and physical make-up of the crust should be conducted concurrently with the pilot studies.

Owens Lake - Test Plot



Wind Direction Frequency Distribution - Test Plot Site
(1981 - 1983)

Appendix B

Participants, affiliation (and specialty) in the Lake Owens Dust Experiment, March 1993

Dust and sand flux source relationships

Dale Gillette	NOAA ARL/ASMD (Research Triangle Park, NC)
Trevor Ley	CIRES, University of Colorado (wind profiles)
Tom Gill	UC Davis Earth Sciences & Resources/ Air Quality Group
Tom Cahill	UC Davis Physics/ Atmospheric Science/ Air Quality Group
Elizabeth Gearhart	UC Davis Air Quality Group
Steve Teague	UC Davis Institute of Toxicology and Environmental Health

Mesoscale modeling

Roland Draxler	NOAA ARL headquarters, Boulder, CO (modeling)

Total dust flux from lake

Tezz Johnson	CIRES, University of Colorado (sunphotometry - south shore)
John Deluisi	NOAA ARL, Boulder, CO (sunphotometers, Mie scattering)
Dave MacKinnon	USGS, Flagstaff, AZ (AVHRR remote sensing)

Dust deposition measurements

Dan Salgado/Brenda Mohn	NAWS, CL (Baker & G1 ,China Lake)
Bill Cox/Duane Ono/Grace Holder	GBUAPCD (Olancha-Inyokern PM_{10})
Carol Breed/ Paula Helm	USGS, Flagstaff, AZ (geomorphology/Geomet tower)
Marith Reheis	USGS, Colorado (soil infiltration measurement)
Vladimir Smirnov	Obninsk, Russia: (aerosol microphysics, electrical effects)

Chemical measurements

Tom Cahill/Jeff Reid	UC Davis Crocker Nuclear Laboratory (PIXE analysis)
Laurent Gomes/A. Gaudichet	CNRS-Universite de Paris (XRF Spectrometry)

Transport, optical characterization, and remote sensing

Jeff Reid	UC Davis Air Quality Group/ Atmospheric Science

Vegetation studies

Mee-Ling Yau	UC Davis Ecology/ Air Quality Group
Mike Brown	UC Davis Air Quality Group
Mike Patterson	Cerro Gordo Freighting Company

Appendix C

Grain Size Analysis of Playa Materials

Samples from the dry surface of the Owens lake bed were taken from southwest of Swansea (May 1991) and from the line of samplers extending into the South Sand Sheet (first week of March 1993).

The sample taken in May 1991 appears to consist almost exclusively of coarse (sand sized, $D>50\mu m$) grains, indicating material from the Swansea dune sands. Only 2% of the total mass lies in PM_{10} size particles.

The materials taken in March 1993 from the South Sand Sheet are quite different. All of the sites except the southernmost show at least one-fifth of their mass in particles 10 microns and smaller, and the six northernmost sites show at least 40% of the total mass in this size range. Less that half the total mass is sand. These six sites (north of the Lake Minerals road), therefore, appear to be composed primarily of fine alluvial (stream-related) or lacustrian (lake-related) sediments with lesser amounts of sand.

These samples were completely disaggregated, and soluble salts, calcium carbonate, and organic materials were completely removed from the sample by dissolution in water, bathing in strong acid, and dispersion in a surfactant solution. The resulting particles consisted of individual mineral grains and silica-cemented rock fragments. These materials were resuspended in a sedigraph (a device used for particle size measurement). All grains larger than 2 mm diameter were removed.

The two southernmost sites (874 m and 1057 m south of the zero point) have more than three-quarters of the mass of surface sediments as indivisible sand grains. This indicates their location on the South Sand Sheet itself, and the importance of this region as a source area of saltating particles which perform natural disaggregation work to release dusts. Note that the more northerly sites on this line -- which contain a higher nominal fraction of fine particles -- have not been reported as a primary source area of blowing dusts. This may well be another indication of the necessity of a large supply of saltating particles for the generation of PM_{10} at Owens (Dry) Lake.

to	2000	1000	500	250	100	50	20	10	5	2	>1
from	1000	500	250	100	50	20	10	5	2	1	
1991 Data											
	23.3	11.9	16	30.3	14.4	1.8	0.4	0.4	0.5	0.3	0.8
m S.	March 1993 Data										
-510	0.6	0.5	8.3	25	11	7.2	7.1	11	15	6	8.8
0	1.5	0.7	5.1	15	7.8	8	9.5	16	17	7.9	12
50	2.3	2.3	6.7	16	8.3	6.6	8.2	14	16	7.4	12
100	0.2	3.3	12	14	5.9	6.9	7.1	13	16	8.6	13
150	1.2	11	20	10	5.3	5.6	5.6	8.8	14	7.2	11
213	1.3	1.9	7.2	14	7.2	8.3	7.4	14	19	9.1	11
282	0.9	2.4	15	23	9	4.7	7.8	10	12	5.7	8.9
521	0.3	6.1	23	24	7.4	4.1	4.2	7	10	5.2	8.9
691	0.4	15	31	20	6.8	2.8	2.8	4.4	5.7	3.6	7
874	0.2	8.1	30	30	7.3	2.2	3	3.9	5.3	3.6	6.8
1057	0.5	8.1	40	25	6.1	2.3	2.5	3.2	4.3	2.7	5.9

Percentage of mass in size intervals (upper and lower in micrometers). Data given for the May 1991 test and the March 1993 tests (by distance south in meters from the zero point).

OWENS LAKE ARB STUDY
MARCH OF 1993
Portable PM-10 Filter Sampler (PFS) Data

SAMPLE	SITE	DATE	START TIME	DURATION	INITIAL FLOW	FINAL FLOW	AVERAGE FLOW	MASS	MASS CONC.	STATUS	PERCENT Uncertainty
				minutes	liters/minute	liters/minute	liters/minute	μg	μg/m3		
TF0003	2T	3/10/93	2:00	120	2.7	2.3	2.5	34	113.33	NORMAL	5
TF0002	2B	3/10/93	2:00	120	2.7	2.7	2.7	66	203.70	NORMAL	5
TF0004	3T	3/10/93	2:00	120	2.7	2.3	2.5	35	116.67	NORMAL	5
TF0005	3B	3/10/93	2:00	120	2.7	2.7	2.7	69	212.96	NORMAL	5
TF0007	4T	3/10/93	2:00	120	2.7	2.7	2.7	69	212.96	NORMAL	5
TF0006	4B	3/10/93	2:00	120	2.7	2.7	2.7	79	243.83	NORMAL	5
TF0011		3/11/93					0	67		Field Blank	
TF0008	2T	3/11/93	12:00	60	2.7	2.7	2.7	270	1666.67	NORMAL	5
TF0012	2B	3/11/93	12:00	60	2.7	2.7	2.7	370	2283.95	NORMAL	5
TF0013	3T	3/11/93	12:00	60	2.7	2.7	2.7	112	691.36	NORMAL	5
TF0009	3B	3/11/93	12:00	60	2.7	2.7	2.7	413	2549.38	NORMAL	5
TF0014	4T	3/11/93	12:00	60	2.7	2.7	2.7	229	1413.58	NORMAL	5
TF0010	4B	3/11/93	12:00	60	2.7	2.7	2.7	513	3166.67	NORMAL	5
TF0015		3/11/93					0	61		Field Blank	
TF0020		3/11/93					0	36		Field Blank	
TF0023		3/11/93					0	53		Field Blank	
TF0017	2T	3/11/93	15:00	120	2.7	1.2	1.95	305	1303.42	NORMAL	20
TF0016	2B	3/11/93	15:00	120	2.7	1.05	1.875	115	511.11	NORMAL	20
TF0019	3T	3/11/93	15:00	120	2.7	1.08	1.89	69	304.23	NORMAL	20
TF0022	3B	3/11/93	15:00	120	2.7	1.13	1.915	45	195.82	NORMAL	20
TF0021	4T	3/11/93	15:00	120	2.7	1.95	2.325	233	835.13	NORMAL	20
TF0018	4B	3/11/93	15:00	120	2.7	1.13	1.915	72	313.32	NORMAL	20
TF0051		3/17/93					0	50		Field Blank	
TF0052		3/17/93					0	42		Field Blank	
TF0053		3/17/93					0	43		Field Blank	
TF0054		3/17/93					0	84		Field Blank	
TF0055		3/17/93					0	41		Field Blank	
TF0056		3/17/93					0	92		Field Blank	

TF0026	1T	3/17/93	15:00	60	2.7	1.3	2	282	2350.00	NORMAL	30
TF0025	1B	3/17/93	15:00	60	2.7	1.7	2.2	721	5462.12	NORMAL	30
TF0028	2T	3/17/93	15:00	60	2.7	1.25	1.975	666	5620.25	NORMAL	30
TF0027	2B	3/17/93	15:00	60	2.7	1.44	2.07	411	3309.18	NORMAL	30
TF0030	3T	3/17/93	15:00	60	2.7	1.29	1.995	412	3441.94	NORMAL	30
TF0029	3B	3/17/93	15:00	60	2.7	1.35	2.025	443	3646.09	NORMAL	30
TF0032	4T	3/17/93	15:00	60	2.7	1.34	2.02	413	3407.59	NORMAL	30
TF0031	4B	3/17/93	15:00	60	2.7	2.35	2.525	507	3346.53	NORMAL	30
TF0106	1T	3/18/93	11:41	90	1.3		1.3	367	3136.75	Q F	40
TF0105	1B	3/18/93	11:41	90	1.7		1.7	612	4000.00	Q F	40
TF0108	2T	3/18/93	11:41	90	1.25		1.25	739	6568.89	Q F	40
TF0107	2B	3/18/93	11:41	90	1.44		1.44	1553	11983.02	Q F	40
TF0110	3T	3/18/93	11:41	90	1.29		1.29	828	7131.78	Q F	40
TF0109	3B	3/18/93	11:41	90	1.35		1.35	686	5646.09	Q F	40
TF0112	4T	3/18/93	11:41	90	1.34		1.34	757	6276.95	Q F	40
TF0111	4B	3/18/93	11:41	90	2.35		2.35	1272	6014.18	Q F	40
TF0114	1T	3/23/93	9:01	120		1.2	1.2	2699	18743.06	Q F	40
TF0113	1B	3/23/93	9:01	120		1.1	1.1	1128	8545.45	Q F	40
TF0116	2T	3/23/93	9:01	120		1.3	1.3	3363	21557.69	Q F	40
TF0115	2B	3/23/93	9:01	120		1.6	1.6	7035	36640.63	Q F	40
TF0118	3T	3/23/93	9:01	120		1.2	1.2	2803	19465.28	Q F	40
TF0117	3B	3/23/93	9:01	120		1.4	1.4	6824	40619.05	Q F	40
TF0120	4T	3/23/93	9:01	120		1.1	1.1	5274	39954.55	Q F	40
TF0119	4B	3/23/93	9:01	120		1.6	1.6	5139	26765.63	Q F	40

OWENS LAKE ARB STUDY

Q F =Questionable Flows = those taken on unstable pumps, and those taken in unsuitable conditions

Field Blank = 58.9 , Standard Deviation = 19

High percent uncertainties in mass concentration are due to progressive storm damage to the samplers

Appendix E
Vegetation Inventory of Owens (Dry) Lake

Species	Family
Aster intrincatus (Gray) Brake	Compositae
Acamptopappus sphaerocephalus (Harv. and Gray) Gray	Compositae
Anemorphis californica (Nutt.) Hook. & Arn.	Sauruaceae
Ambrosia dumosa (Gray) Payne **	Compositae
Artemsia spinescens D.C. Eat.	Compositae
Atriplex hymenlytra (Torr.) S. Wats.	Chenopodiaceae
Atriplex confertifolia (Torr. & Frem). S. Wats.	Chenopodiaceae
Atriplex parryi S. Wats.	Chenopodiaceae
Atriplex polycarpa (Torr.) S. Wats.	Chenopodiaceae
Atriplex torreyi (S. Wats.) S. Wats.	Chenopodiaceae
Bassia hysspifolia (Pallas) Scribu.	Chenopodiaceae
Chrysothamnus nauseosus (Torr.) Scribu. *	Compositae
Distichlis stricta (Torr.) Scribu.	Gramineae
Eriogonum inflatum Torr. & Frem.	Polygonaceae
Encelia frutesens var virginensis (A. nels.) Blake **	Compositae
Ephedra navadensis S. Wats.	Gnetaceae
Grayis spinosa (Hook.) Moq.	Chenopodiaceae
Heliathus annus L.	Compositae
Hymenoclea salsola Torr. & Gray **	Compositae
Juncus balticus Willd	Juncaceae
Carex douglasii Boott.	Cyperaceae
Lycium andersonii Gray	Solanaceae
Petalonyx nitidus S. Wats.	Loasaceae
Psorothamnus aborescens var. minutifolius (Parish) Barneby	Papilliaceae
Sarcobatus vermiculatus Nees *	Chenopodiaceae
Cripus acutus Muhl. Ex Bigel.	Cyperaceae
Sporobulus airoides (Torr.) Torr.	Gramineae
Stipa speciosa Trin. & Rupr.	Gramineae
Suaeda torreyana S. Wats. Nomen Superfl	Chenopodiaceae
Tamarix ramosissima Ledeb	Tamaricaceae
Vulpia octoflora (Walter). Rydb.	Gramineae

* Great Basin species. ** Mojave Desert species.

Major species found within LADWP mapping units around Owens Lake Playa (mostly around the historic shoreline 1083 m above mean sea level).

Site**	Stand	N	% cover* *Distichlis spicata*	*Nitrophilus occidentalus*	*Atriplex parryi*	*Tamarix ramosissima*	*Scirpus robustus*	Bare ground
Ksp	D1	15	51.33	0a	0a	0	0a	48.67
			+3.50f					+3.50c
Ksp	DN1	90	65.89	3.52	0a	0	0a	27.62
			+2.65e	+0.88c				+2.73b
Ksp	SCRO	50	0a	0a	0a	0	89.85	9.53
							+1.86b	+1.91a
Tsp	ATPA	55	7.12	1.27	9.1+	0	0a	78.41
			+1.44c	+0.5b	2.34c			+2.86d
Tsp	DN1	100	30.91	16.79	0a	0	0a	48.96c
			+2.47d	+1.763				+2.04
Tsp	T1	25	2.28	7.86	2.42	12.69*	0a	87.20

*Percentage cover of *Tamarix* is calculated by point-centered method; Turkey Test not performed.
** Ksp = Keeler Spring: Tsp = Tamarix Spring

Mean covers (and S.E.) of major species found in each vegetation stand. Mean covers followed by different letters are significantly different at 0.05 level following the Turkey multiple range statistical test (Zar, 1985)

			pH				EC (mmhos/cm)			
Site	Stand	N*	0-15	0-5	5-15	15-30	0-15	0-5	5-15	15-30
Ksp	D1	3	10.1			9.60	6.33	/	/	1.97
			+.06b	/	/	+.12ab	+.82a			+.63a
Ksp	DN1	6	9.78			9.40	5.47	/	/	1.12
			+.04a	/	/	+.12a	+.78a			+.27a
Tsp	DN1	20	10.12			9.92	7.22	/	/	2.17
			+.04b	/	/	+.02b	+.57a			+1.42a
Tsp	ATPA	11	/	9.66	9.88	9.84	/	4.46	12.34	6.98
				+.06a	+.03a	+.03b		+1.10a	+4.51a	+.87c
Tsp	T1	5	/	9.86	9.90	10.14	/	15.93	20.22	4.84
				+.11a	+.21b	+.24b		+6.11b	+7.14a	+5.02b

*N is not the same for all stands and is sometimes smaller due to missing samples.

Mean pH and EC (mmho/cm) with S.E. of vegetation stands at Keeler Spring (Ksp) and Tamarix Spring (Tsp). Numbers followed by different letters are significantly different at 0.05 level following the Turkey multiple range statistical test (Zar, 1985). Soil samples at Ksp and TspDN1 were only divided into two depth levels (0-15 cm and 15-30 cm).

Appendix F

SAGA OF INYO COUNTY

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Chapter 183
SOUTHERN INYO
AMERICAN ASSOCIATION OF RETIRED PERSONS

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OWENS VALLEY TODAY

By Beveridge R. Spear

In the spring of 1976, Robert Blair, of Lone Pine and I made a tour of the country. A heavy south wind was blowing, and huge billowy dust clouds from dry Owens Lake filled the air.

From Lone Pine we drove east through Keeler on the Death Valley highway turning north on the Saline Valley road, then northeast on the Hunter's Ranch Mountain road. A haze hung over the eastern slope of the Inyo range. We surmised it to be soda dust from Owens lake.

To verify this we drove from Lee Flat, on the eastern slope, through Saint Lucas canyon to Cerro Gordo. Here we parked our car, and hiked three miles north along the main ridge of the Inyos. My Dad mined here 85 years ago, hence it was familiar ground.

The elevation varied from 8,500 to 9,200 feet. Some of the Pinon trees looked silvery-white and unnatural. We found them covered with soda dust. Our trousers were streaked with the dust when we brushed by.

But more surprising, little plants and scrub bushes only an inch to three inches tall were edged with the dust. This was especially noticeable on the main ridge where the wind swept over to the east side from whence we had just come.

How long can vegetation survive this soda-alkali dusting process every time a high wind blows? This would make an interesting study for botanists of the Department of Water and Power. Mrs. Mary DeDecker, one of the original consultants reported these dangers long ago. We understand her reports were ignored.

Laurence Odel, operation specialist for the Great Basin Unified Air Pollution Control District said, the City's right to take the water from the valley "Does not give them the right to pollute the air also. What they are doing here is environmental homicide."

Duane Georgeson, engineer for the Los Angeles Aqueduct said, "It comes down to a question of benefiting three million people in Los Angeles or 15,000 people in Owens Valley." This is the same argument used by Caiaphas, the high priest, who said, "It's better for one man to die than for a whole nation to perish."

The Press recently quoted Mayor Tom Bradley as saying, "Los Angeles has no intention of making Owens Valley a dust bowl." Should the mayor take the 125 mile drive in a windstorm as we did, then motor around the dry lake he would cover about 190 miles. Mr. Bradley would see the dust clouds billowing as high as the Inyo mountains. He would smell and taste the stuff.

Southern Owens Valley is already a dust bowl! A lost Paradise — another Death Valley in the making.

It seems that nature responds with more precipitation where vegetation flourishes. Seventy-five years ago the Sierras were packed with perpetual snow. Now they appear bare and drying up.

This year a cattleman told us his high Sierra summer range was dry until rain fell in July, and started the grass growing. What's happening to those beautiful summer meadows of Redtop and Timothy grass, scattered among the canyons and high valleys of those beautiful mountains? Dry instead of green, after a winter of snow! Could this be a handwriting on the Wall?

More water pumped from the valley floor creates more surface desert, and more extensive dust storms, and less precipitation may be expected. This has been the pattern for decades past.

The generation of local Indians we knew are gone. A few of their children live on the reservation near Lone Pine. We asked one widow why they didn't take better care of their gardens and fruit trees. She answered, "The City promises us irrigation water but it doesn't always come. The gardens die, and we can't do anything about it."

Appendix G

The Ecology of Dune

Except from *DUNE*, by Frank Herbert. Ace Books, Inc., New York (1965)

Dedication: To the people whose labors go beyond ideas into the realm of "real materials" -- to the dry-land ecologists, wherever they may be, in whatever time they work, this effort at prediction is dedicated in humility and admiration.

Dune Appendix 2:

pg. 508 ff...

............The concern on Arrakis (the Desert Planet) was not with water, but with moisture.

. . .

............Then Kynes (the Imperial Planetary Ecologist - ed.) saw the salt pan.

His 'thopter, flying between stations far out on the bled, was blown off course by a storm. When the storm passed, there was the pan - a giant oval depression some three hundred kilometers on the long axis - a glaring white surprise in the open desert. Kynes landed, tasted the pan's storm-cleaned surface.

Salt.

Now, he was certain.

There'd been open water on Arrakis - once....

pg. 510 ff..

. . . . dust (the truly omnipresent problem there) is produced by the constant surface creep, the "saltation" movement of sand. Coarse grains are found on the downwind sides of dunes. The windward side is packed smooth and hard. Old dunes are yellow (oxidized), young dunes are the color of the parent rock - usually gray.

Downwind sides of old dunes provided the first plantation areas. The Fremen (local Bedouins - ed.) aimed first for a cycle of poverty grass with peat-like hair cilia to intertwine, mat and fix the dunes by depriving the wind of its big weapon: movable grains.

. . . . The mutated poverty grasses were planted first along the downwind (slipface) of the chosen dunes that stood across the path of the prevailing westerlies. With the downwind faces anchored, the windward face grew higher and higher and the grass was moved to keep pace. Giant sifs (long dunes with sinuous crest) of more than 1500 meters height were produced this way.

When barrier dunes reached sufficient height, the windward faces were planted with tougher sword grasses. Each structure on a base about six times as thick as its height was anchored - "fixed."

Now, they came in with deeper plantings - ephemerals (chenopods, pigweeds, and amaranth to begin), then scotch broom, low lupine, vine eucalyptus (the type adapted for Caladan's northern reaches), dwarf tamarisk, shore pine - then the true desert growths; candellila, saguaro, and bis-naga, the barrel cactus. Where it would grow, they introduced camel sage, onion grass, gobi feather grass, wild alfalfa, burrow bush, sand verbena, evening primrose, incense bush, smoke tree, creosote bush.

They turned then to the necessary animal life - burrowing creatures to open the soil and aerate it: kit fox, kangaroo mouse, desert hare, sand terrapin . . . and the predators to keep them in check: desert hawk, dwarf owl, eagle and desert owl; and insects to fill the niches these couldn't reach: scorpion, centipede, trapdoor spider, the biting wasp and the wormfly . . . and the desert bat to keep watch on these.

"The thing the ecologically illiterate don't realize about an eco-system," Kynes said, "is that it's a system. A system! A system maintains a certain fluid stability that can be destroyed by a mis-step in just one niche. A system has order, a flowing from point to point. If something dams that flow, order collapses. The untrained might miss that collapse until it was too late. That's why the highest function of ecology is the understanding of consequences."

Appendix H

INSTRUMENTS AT EACH SAMPLING SITE, MARCH 1993

NOAA/UCD LINEAR ARRAY AND GEOMET,
OWENS (DRY) LAKE AEROSOL STUDY

SITE CODE	LINEAR DISTANCE (meters)*	INSTRUMENTATION
H1	0	BSNE saltating particle monitors at 0.1, 0.2, 0.3, 0.5, 0.6, 1.0 m Anemometers at 0.2, 0.5, 1.0, 3.0 m PFS aerosol samplers at 0.6 and 3.0 m, on and after March 17th
H2	50	BSNE saltating particle monitors at 0.1, 0.2, 0.3, 0.5, 0.6, 1.0 m Anemometers at 0.2, 0.5, 1.0, 3.0 m PFS aerosol samplers at 0.6 and 3.0 m
H3	100	BSNE saltating particle monitors at 0.1, 0.2, 0.3, 0.5, 0.6, 1.0 m Anemometers at 0.2, 0.5, 1.0, 3.0 m PFS aerosol samplers at 0.6 and 3.0 m
H4	150	BSNE saltating particle monitors at 0.1, 0.2, 0.3, 0.5, 0.6, 1.0 m Anemometers at 0.2, 0.5, 1.0, 3.0 m PFS aerosol samplers at 0.6 and 3.0 m
ROAD	196.1	BSNE saltating particle monitors at 0.2, 0.5, 1.0 m [Note: This point is on N side of the Lake Minerals Co. road across the lake bed]
I1	213.2	BSNE saltating particle monitors at 0.2, 0.5, 1.0 m [Note: This point is on S side of the Lake Minerals Co. road across the lake bed]
I2	282.2	BSNE saltating particle monitors at 0.2, 0.5, 1.0 m
S1	521	BSNE saltating particle monitors at 0.1, 0.2, 0.3, 0.5, 0.6, 1.0 m Anemometers at 0.2, 0.5, 1.0, 2.0 m, on March 11th only Wind direction indicator SENSIT sand motion sensors at .05, .10, .30, .50 m
I3	691	BSNE saltating particle monitors at 0.2, 0.5, 1.0 m
	703	[Note: This point is where the line crosses gap in WESTEC sand fences; no equipment was present at this point, however]
S2	874	BSNE saltating particle monitors at 0.1, 0.2, 0.3, 0.5, 0.6, 1.0 m SENSIT sand motion sensors at .05, .10, .30, .50 m
S3	1056.8	BSNE saltating particle monitors at 0.1, 0.2, 0.3, 0.5, 0.6, 1.0 m Anemometers at 0.2, 0.5, 1.0, 2.0 m, on and after March 18th SENSIT sand motion sensors at .05, .10, .30, .50 m [intermittent data]
Geomet	1900, [and 2150 m East]	U.S. Geological Survey Geomet tower (McCauley *et al.*, 1984). Solar powered remote sensing of meteorological data including anemometers, thermometer, precipitation gauge; also includes BSNE saltating particle monitors and SENSIT saltation sensors

*Linear distance due south of boundary between efflorescent crust and sand on south Owens sand sheet. The array was oriented along a (true) north-south line.

APPENDIX I

CONTROL OF PM_{10} DUST EPISODES FROM OWENS (DRY) LAKE

The results presented in the body of this report, along with additional observations of the investigators during this project, when taken together with earlier work, have clarified the relationship between meteorology, lake bed surface conditions, and dust generation at Owens (Dry) Lake. This lays the basis for strategies for dust reduction and dust mitigation, and in this appendix we discuss how such strategies might be implemented.

1. Meteorology

The most important single factor in dust generation from the playa of Owens (Dry) Lake is meteorology. If the wind velocity is low (generally below about 7 m/s measured at several meters height), there is little or no dust from the playa. Since low wind conditions are common, then air quality can be superb; this is shown by the excellent PM_{10} air quality at sites near the lake bed, such as Keeler, on roughly 90% of all days (Tables I and VII).

While there is no way to modify large-scale meteorology, there are ways to modify the micrometeorology of the wind just above the playa surface. The key factor is that Owens (Dry) Lake is very large in extent and a very flat surface. The lake bed topography allows extreme values of wind shear to occur, where 90% of full wind velocity occurs on the orders of centimeters above the surface (Barone *et al.*, 1979, 1981; Kusko and Cahill, 1984; this report). There are techniques which involve increasing surface roughness and hence raise the Z_0 value from the extremely low values seen in these studies to something more reasonable. For example, this can be accomplished naturally by the presence of vegetation, which forces the wind up away from the ground and thus reduces wind shear on the friable surface (Kusko and Cahill, 1984; Buckley, 1987; Stockton and Gillette, 1990).

Mitigation techniques based on wind shear reduction include all the ways to increase surface roughness, which have included railroad ties, broken asphalt, etc. in the past, trenching and mounding of the surface topography (as occurs presently in the Lake Minerals Co. operations at Owens (Dry) Lake), sand fences and other semi-porous structures, and artificially enhanced vegetation.

2. Surface Modification

The second most important factor in dust generation is the nature of the playa surface. This study, and many others dating back to the 1970s (Reinking *et al.*, 1979; Barone *et al.*, 1979; WESTEC, 1984; Saint Amand *et al.*, 1986) have shown that the PM_{10} dust generated by Owens (Dry) Lake is a mixture of fine clastic sediments (clays and silts) and fragments of broken salt crust. Clearly, if this material were removed, covered up, or modified, then PM_{10} dusts would decrease and, in the limit, vanish.

Mitigation techniques based on surface modification include first and foremost covering the playa up with water. This was the obvious solution for Mono Lake, where water resources were available (Kusko and Cahill, 1984). For Owens (Dry) Lake, the water requirements are extreme, on the order of 250,000 acre-feet per year (AF/yr). Further, little benefit would be gained from the first 80,000 AF or so, since the lowest third of the playa is not a significant producer of dust. It would also drown out the existing leaseholder (Lake Minerals Co., which leases the site from the California State Lands Commission), with lost income to the local economy and the State.

Therefore, methods were sought to "perch" water on the dust-producing areas of the Owens playa. We proposed laser-leveled ponding in our report to the Air Resources Board ten years ago (Kusko and Cahill, 1984), and the GBUAPCD is using uncontrolled flooding in a present large-scale mitigation test. Both methods have potential, but appropriate resource use still needs to be established. Clearly, flooding or ponding two-thirds of the playa for an entire year would use roughly 160,000 AF/yr of water (which, though, could be saline or semi-saline and thus not otherwise available for human use). However, there are ways to reduce the area affected and the amount of water used, although at some loss of control efficiency.

Other surface modification methods include covering the playa with some material such as gravel, an artificial coating, or other analogous materials. The requirements for maintenance of these methods become critical, however, especially in light of the problem of surface abrasion by moving sand. Once a gravel coating or other such layer is covered by sand, it becomes ineffective if any pathway exists for saline groundwater to move towards the surface and deposit efflorescent salts.

Our data make clear that the playa modifies itself after being wetted by rains, forming a sturdy crust that resists dust formation. This is a result of the high salt content of the playa surface, and offers an intriguing method for dust mitigation. If there were a method for protecting playa surface crusts from destruction, then dust production would decrease sharply. Our data indicates that the destruction of the crust is generally caused by the motion of coarse sand and fragments of already-broken crust across stable saline crust. We must reiterate that this study was deliberately performed in an area pre-selected to have significant sand motion and high dust production, so we must be cautious in attempting any extrapolation to other sites on the lake bed; however, the correlation between sand transport and dust production is excellent, especially for the largest events.

3. Sand Control

Motion of sand across the crust and the generation of PM_{10} dusts was documented in detail as it happened for the first time in this project. In case after case, year after year, from the early work of Gillette *et al.* (1980, 1982; Gillette, in WESTEC, 1984) to the present study, investigators have found that the crust by itself resists dust formation even at extreme wind velocities. During this study, one could see the crust break up progressively with time as the year progressed in 1991 and 1992 and day by day in March 1993, with beige-gray patches of sand and silt growing into the white areas of salt crust. We saw a rainstorm arrive on March 25, 1993, forming a new crust which we have labeled "cemented crust," with undifferentiated salt, sand and silt overlying a dry, salty sand- silt mixture, unlike the efflorescent crusts of spring that are in direct contact with moisture.

The results of the Phase II studies of 1987- 1988 were crucial in showing that not all areas of the lake bed experienced sand motion and that the amount of sand moved in a given year was actually quite modest. Measurements made in GBUAPCD's sand transport samplers (Figures 6a and 6b) showed that the maximum annual sand motion for the period was roughly 10 cubic yards per foot-wide path (Note: these were the measurement units used in their study), confirmed by the rate at which sand built up behind three sets of sand fences. It also showed areas in which moving sands were rarely present, although in the largest storms sand has been observed to move entirely across and off the lake bed and form into dunes well above the elevation of the playa in the surrounding foothills (Patterson, 1993). In addition, objects found on the playa during this study (survey markers, old structures or abandoned equipment, partially embedded fulgurites, etc.) indicate that significant net amounts of inflation or deflation are not observed over the past decades.

Sand control can be achieved by suppressing sand sources and capturing sand once it begins to move in saltation. Sources of sand include some that are not presently on the playa itself, including the Olancha Dunes, southeast of Olancha and more than a kilometer from the present lake bed. These dunes were directly observed by the investigators to be contributing sand onto the playa during the March 1993 LODE intensive. The Dirty Socks Dunes on the lake bed contain sand which preliminary investigations show to be very similar to that of the Olancha Dunes- i.e., low in salt and non-crusting. These can be important sources of saltating particles to the playa, especially the South Sand Sheet, especially when the rest of the lake bed is armored against wind erosion by crusts. Other sources of surface disturbance include off-road vehicles, tailing piles, etc., while in the strongest winds almost all parts of the lake bed can actively erode, including the tops of artificial dunes.

Data from this study, as well as subsequent investigations and review of the LODE dataset by others, show that saltation of sand occurs predominantly within 30 cm of the playa surface (Cahill *et al.*, 1993, 1994; Fryrear, 1994), and thus would be clearly affected by any reduction in wind speed caused by vegetation, sand fences, or other surface obstructions. Sand motion is also terminated in any open water body, even if fairly narrow in extent (GBUAPCD suggests approximately 10 to 15 meters, based on their flooding study).

The degree of control of PM_{10} dust by control of sand motion was the focus of a more extensive project (California State Lands Commission Contract C-1975, involving many of the same investigators as this ARB study) which began in spring 1993 (Cahill *et al.*, 1993) and continued into 1994. While the final report of this study is not yet available, some results can be discussed. This project did achieve low-cost sand fences, long-lived sand fence designs color matched to lake bed sediments, and included a new, gapped fence design (White and Cho, 1994) that reduces fence cost by unit control by more than 30%. Control of sand motion in a test array of more than 1670 meters on the South Sand Sheet, just south of the LODE March 1993 intensive test site, showed excellent control (greater than 90%) of sand transport from even a single fence (Figure 55). Finally, local PM_{10} generation rates were strongly suppressed in the areas where fences stopped sand motion and protected the surface crusts, or in parts of the test array in which the crust never broke up.

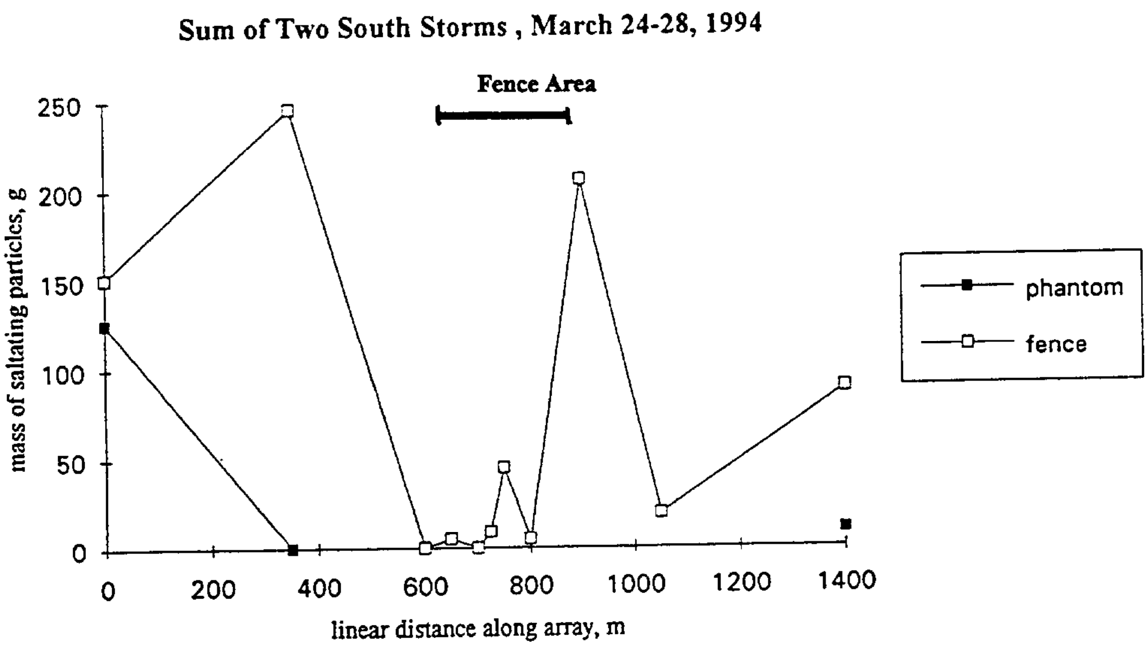

Figure 55. Example of the effect of sand fences on sand motion, Owens (Dry) Lake South Sand Sheet mitigation test, March 1994 (California State Lands Commission Contract No. C-9175, preliminary data).

The control of saltating sands on Owens (Dry) Lake via the use of sand fences to create dunes also has important ancillary benefits in its ability to provide an environment that is more amenable to the permanent establishment of vegetation on the playa. Dahlgren (1993) reported,

> A minimum of 70 cm of oxidized soil is required to support stressed vegetation and a minimum of approximately 1 m of oxidized soil appears necessary to support relatively healthy vegetation. While high total salt and boron concentrations are present on several non-vegetated sites, these salts could be easily leached from the soil profile with proper irrigation management. The additional problem associated with sand blasting of vegetation appears to be manageable over large portions of the lake bed. Therefore, we conclude that vegetation establishment is possible over much of the playa if the effects of shallow anoxic groundwater are alleviated. Nature verifies this conclusion as shown by the successive vegetation establishment on the lower beach remnants as the groundwater has fallen with the lake level. The establishment of artificial dunes using fences appears to be the most scientifically sound and economically feasible method for establishing the necessary rooting zone for successful propagation of native vegetation.

4. Optimum control strategies for Owens (Dry) Lake PM_{10} suppression

The results of these studies now allow us to modify, quantify and extend the proposal we made for overall dust control at Owens (Dry) Lake to the California State Lands Commission (owner of most of the lake bed) in August, 1991 (Owens Lake Task Group, 1991). This document, based largely on earlier projects sponsored by the Air Resources Board and State Lands Commission at Owens and Mono Lakes, had as its goals the suppression of dust and reclamation of the public trust values of the area. The latter takes into consideration some dust control methods earlier proposed by the GBUAPCD and their contractors (Aerovironment Corp., 1992) which were deemed not acceptable by the SLC in their correspondence to the GBUAPCD, included in the latter agency's BACM SIP for the Owens Valley PM_{10} planning area (GBUAPCD, 1994).

The focus of the 1991 Owens Lake Task Group proposal was to identify ways in which the Owens Lake Bed was presently limiting dust emissions and artificially enhance those processes. The ecological endpoint for most of the lake bed would be the vegetation-stabilized dune fields seen at the margins of Owens and Mono Lakes (and other similar ecosystems) which, due to the control of wind shear, have a much higher threshold wind velocity for dust emission. Other endpoints include an active wet area of the Owens River delta, marshlands from semi-saline springs and the like, and (of course) permanent surface water after the termination of mineral extraction operations.

The 1991 proposal proposed four specific types of mitigation required to meet these endpoints:

1. An enhanced Owens River delta, with several vegetated channels well separated from each other.

2. Riparian corridors (artificially enhanced meandering wetlands supported by some semi-saline water), protected by vegetated and unvegetated dune fields, so aligned as to cut the wind fetches in the sand-dominated areas.

3. Dry dune fields, stabilized and meandering dune areas modeled on those occurring near Mono Lake, but without anthropogenically-introduced and artificially-maintained vegetation. In both of the cases above, some partially filled sand fences would be at the outer extremes of the dune fields to trap residual sand.

4. A modest Owens Lake at the area of the Lake Minerals Co. operation after the termination of present mining activities. We propose that the final phases of mining leave a lake with islands. With some addition of water, the plan would be to achieve high brine shrimp (*Artemia*) populations and populations of breeding and migratory waterfowl.

The present ARB-sponsored study and the companion SLC contract have greatly enhanced our ability to make detailed plans with realistic costs and realistic estimates of the levels of dust suppression that would be expected. In summary, we have found that most of the prior experience of the investigations at Mono Lake was relevant to Owens (Dry) Lake, and that an ecologically sound and cost-effective mitigation strategy is possible. We are pleased that many of our ideas are incorporated into the June 1994 BACM SIP of the GBUAPCD. Our techniques, when implemented, would be acceptable to the State of California, which is the landowner of Owens (Dry) Lake. A revision of the 1991 proposal is in progress as part of the State Lands Commission contract, and is due to be completed in autumn 1994.